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Heat Exchangers: An Investigation into the Operability & Performance

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Submitted: 25/4/ 2017

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Acknowledgement

I would like to thank MR: Robert Goodson for supervising me during the project, as his comments and feedbacks were brighten my path towards completing this project.

I would like to thank my father who was very supportive and stood with me since I started my studying and until now. Many thanks to all laboratory staff who were very helpful to me when I did my experiments.

Abstract

Heat Exchangers are an important component for many devices, with their performance enhancement being continuously pursued. The purpose of this report is to investigate and understand the performance parameters of Heat Exchangers. With focus on the efficiency and heat transfer coefficient parameters, whilst studying how they behave when changing the mass flow of air, water, heater temperature and configuration of the heat exchanger itself. Many research papers found through literature review indicate that these values are most likely to change the behaviour of the Heat Exchanger and that a compromise must be found for best performance. The experiment was conducted using the TD1007 water to air Heat Exchanger, as this was the only available machine for use. The manual provided with this Heat Exchanger was heavily used throughout the study as it provided the essentially formulas and theory. The study finds that all these parameters do in fact effect the performance of the Heat Exchanger. Surprisingly, the best performing Heat Exchanger was found to be the 16 tube configuration with a water flow of 0.033kg/s with an air mass flow of 0.1166 kg/s and heater temperature of 60°C. This had given a Heat Transfer Coefficient of $0.193 \frac{W}{m^2K}$ with an efficiency of 12.1%. Further investigations should look at doing the experiment on a different type of Heat Exchanger and the surface area of the Heat Exchanger itself.

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List of Symbols

U = Heat Transfer Coefficient (W/m^2K)

$\dot{Q}$ = Rate of Heat Transfer (W)

A = Heat Transfer Area (m^2)

$LMTD$ = Log Mean Temperature Difference (K)

$\dot{m}$ = Mass flow rate (kg/s)

c_p = Specific heat capacity (J/kg/K).

ΔT = Temperature Difference (K)

C_d = Discharge Coefficient of the Orifice

A_0 = Orifice Area (m^2)

Δp = Orifice Pressure Drop (Pa)

ρ = Density (kg/m³)

C_{EB} = Energy Balance Coefficient

η = Temperature Efficiency (%)

$\bar{\eta}$ = Mean Temperature Efficiency (%)

1a = 32 tube configuration varying the water mass flow

1b = 32 tube configuration varying the air mass flow

1c = 32 tube configuration varying the heater temperature

2a = 16 tube configuration varying the water mass flow

2b = 16 tube configuration varying the air mass flow

Chapter 1

Introduction

1.1 Background of the issue

A Heat Exchanger (HX) is a device found in many of today's industrial and commercial technologies, for example air conditioners, air plants and refrigerators. A Heat exchanger is a very important component found in those technologies. It is used to transfer heat between two media (Lienhard, 2011). It is important that heat exchangers are efficient, reliable and provide cooler or warmer air, depending on what is needed (Detzer et al, 1994). This means Heat Exchanger efficiency and performance is important to examine.

This report will discuss how Heat Exchangers are best used by investigating and understanding how to maximum performance and efficiency. This will be done by using a bench top heat exchanger to perform experiments to get an outcome, focusing on air variation, water flow variation and the heat transfer area. Once completed, the dissertation will then analyze the behaviour of the Heat Exchanger under different parameter changes, explaining how they impact on its performance. It will also be noted which Heat Exchanger configuration the best was in regards of its performance. Finally, the dissertation will compare the results of the experiments to the theory of heat exchangers.

Following on from the Introduction, the aims and objectives of the dissertation will be discussed. Next will be the literature review, methodology and theory. The next section will discuss the results of the experiment and will end with concluding remarks overall in regards to the dissertation.

1.2 Aim and Objectives

The aim of this project is to identify the behaviour of the Equipment TD1007 Heat Exchanger, under different parameter changes and to analyze its performance and efficiency. Aims and objectives should be achievable and in a time limits (Thomson, 2017). Below is a breakdown of each aim and objective, explaining how they will be achieved.

1. Ensuring the project is viable by literature review.

A literature review is a necessary component of this dissertation, in order to outline the current uses of Heat Exchanger and to identify gaps of knowledge where efficiency is concerned.

2. Understand how heat exchangers operate and function.

This report also seeks to understand the operability and functionality of Heat Exchangers, by focusing on the choice of heat exchanger and also the methodology in which the experiments will be conducted. This will be done by studying, calculating, optimizing and testing a basic Heat Exchanger with focus on operability and performance.

3. Develop a mathematical model of measurement

To apply material learned in thermodynamics, fluid mechanics and heat transfer. This will be achieved by investigating the theory of heat transfer coefficient as a way to differentiate between different heat exchanger configurations.

4. Obtain performance data.

Various Heat Exchanger configurations will be tested in a laboratory. This is in order to identify best performance.

5. Further amend mathematical model for improved performance.

Based upon the results generated, the mathematical model will be amended in order to enhance performance.

6. Acknowledge and outline limitations found and their reasons.

This will be achieved comparing the results of each configuration and analyzing them against each other and the theory discussed within the literature review.

1.3 Timing plan

Week No. from 26/09/2016 to 05/05/2017

Activity	w1	w2	w3	w4	w5	w6	w7	w8	w9	w10	w11	w12	w13	w14	w15	w16	w17	w18	w19	w20	w21	w22	w23	w24	w25	w26	w27	w28	w29	w30	w31	w32
Literature review																																
Project proposal																																
Understand HX efficiency and operability																																
Project poster																																
Outline the mathematical methods																																
Preparation of interim viva																																
Initial computational model testing																																
Further adjustments and recommendations																																
Preparation for second poster																																
Computational/lab testing of final research																																
Obtain results and improve																																
Dissertation writing																																
Project presentation																																

Chapter 2

A Review of the Literature

2.1 Introduction

To have a full understanding of Heat Exchangers, a literature review is conducted so that a good familiarity with current and past thinking on the topic as well as work done to date. This part of the paper helps justify future research and work based on what has been done and concluded previously. In order to do this, a detailed investigation of various papers must be analyzed, criticized and discussed to conclude a scope of work and help identify a gap in the research which can be further explored. To best explore the problems surrounding Heat Exchangers a set of questions is to be answered based on literature:

1. What are the uses of Heat Exchangers (Applications and mechanics)?
2. What issue has been raised previously and currently concerning Heat Exchangers?
3. What has been or is being done to counter this problem?
4. How successful has the solution been if any (is it consistent, can it improved further, what are the limitations etc.)?

2.2 What are the uses of Heat Exchangers?

The main outcome of a Heat Exchanger is to convert heat between two media; be it gas to gas, liquid to liquid or the two mixed (Thulukkanam, 2013). For instance, a radiator found in a combustion engine is used to cool hot water using a flow of air. It is used for both heating and cooling applications and can be found in machines such as Refrigerators, Air Conditioners, Combustion Engines and so forth (Thulukkanam, 2013). Without the use of Heat Exchangers, it would have an inefficient energy process and would not be able to minimize losses (Carswell, 2016).

For example, a typical air conditioner (AC) consists of: a blower, cooling coils, a compressor, air filter, condenser coils and condenser fan (Hadhazy, 2013). Warm atmospheric room air is

drawn into the AC and blown over the cooling coils to remove the heat and is then blown out as cool air (Hadhazy, 2013). This is where the Heat Exchanger lies and exchanges the heat, in this case from warm to cool air. The heat that is absorbed by the cooling coils are then blown outdoors as useless air. When a liquid is turned into a gas it absorbs heat. Also, when a gas is compressed into a liquid it releases heat (Hadhazy, 2013). As warm air flows over the cooling coils, it causes the liquid in the coils to evaporate. The evaporated condensed gas has

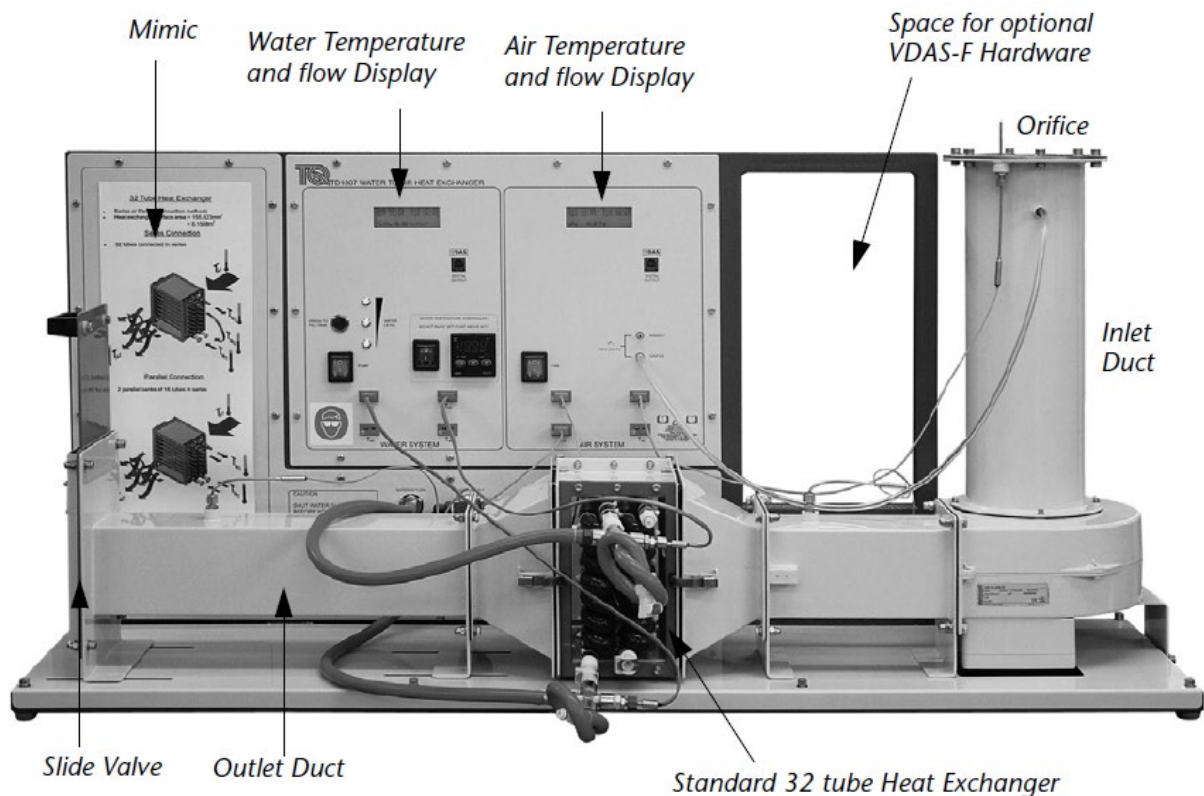


Figure 1 - TD1007 water to air Heat Exchanger (TD1007 Heat Exchanger – User guide)

a great deal of heat which is cooled and turned into a liquid when introduced to room air. This is then passed on to the cooling coils and the process continues(Hadhazy, 2013).

To summarize, Heat Exchangers are an important component used in multiple systems. Without it many processes are useless or inefficient. Numerous machines are reliant on this device to carry out their objectives, i.e. an Air Conditioner.

2.3What issue has been raised concerning Heat Exchangers?

There are dozens of scientific journals concerning Heat Exchangers including the basic design of, its functionality, selection and efficiency. One publication by Tom Higley in 2016looks into the common problems faced with Heat Exchangers. He notes that poor Heat Exchanger performance can be from any of the factors: vibration, exchanger leakage, increasing exchanger

energy consumption, pass partition bypassing, air cooler air recirculation and fouling (Higley, 2016). However, Kern in 1965 states in his publication that “Heat Exchanger performance can deteriorate with time, off design operations and other interferences such as fouling, scaling etc.” (Kern, 1965).

As some of the raised problems are based on wear and age the focus must be on the aspects that can be controlled such as energy consumption or off design operations. This can relate to the efficiency of the Heat Exchanger which can be affected over time (Kern, 1965). Hence, a main concern about almost any engineering machine is efficiency. According to the Oxford dictionary, it is defined as “achieving maximum productivity with minimum wasted effort or expense” (Oxford Dictionaries, 2017) especially in machine terms. It is the comparison of the real and best performance of a machine (Fakheri, 2007).

It is known from the second law of thermodynamics that as energy is transformed or transferred then more and more of it is wasted (Fakheri, 2007) (“Transfer of Energy Between Trophic Levels”, 2017). A Heat Exchanger’s efficiency can be defined in many ways, however in terms of thermal performance there are a few factors that should be considered (“What Is a Heat Exchanger?”, 2014):

- **Flow rate** – a greater flow rate will increase the capability of the exchanger to transfer heat. However, a greater flow rate also means more mass therefore difficulty in removing energy as well as velocity increase and pressure loss.
- **Temperature differential** – the difference between the cold fluid and hot fluid is essential. This is as lower cooler temperatures will extract more heat out of hot fluid than if it were warm. That is the ratio between the hot and cold fluid.
- **Compressor and materials** – the components that are used to turn a gas into and liquid and so on must work at optimum. This is to ensure that the previous mentioned point is achieved. Therefore, how much the compressor can compress defines this. Furthermore, the material selected for heat transfer must not increase or decrease the temperatures of the fluids unintendedly. For example, copper is ideal for the cold fluid as it maintains its temperature.

The problem faced by Heat Exchangers is an issue of thermal efficiency as mentioned by Fakheri in 2007. Although it is also dependent on factors including fouling, leaks, choice of material as so on, efficiency is an issue that must be resolved by mechanical means. Energy

losses are an occurrence that cannot be stopped as known from the second law of thermodynamics.

2.4 What has been done to counter the issue?

Ideally, it is wanted that no heat transfers within the system (loss of heat or cold fluid warming), this is not the case and it always has heat transfer occurring where it is not desired ("Transfer of Energy Between Trophic Levels", 2017). However, methods have been designed to try and improve the efficiency by minimizing the losses. An invention by William L. Keith and Kimberly M. Cipolla meant that efficiency was improved by the introduction of a vortices generator (Kasischke, 2002). This was done by "the use of external fins or the like. In other instances, a structure is placed in the tube to generate vortices or turbulence within the tube to increase heat exchange" (Kasischke, 2002). This work has been confirmed and agreed by other scientists also; one publications notes that these vortex generators disrupt the thermal boundary layer and therefore increases heat transfer rate (Chormale et al, 2011).

Other solutions include changing the Heat Exchanger flow pattern. Researchers have found out that by changing the flow pattern it affects required Heat Exchanger surface (Bengtson, 2010). There are three main types of Heat Exchanger flow patterns, they are the Parallel flow, Cross flow and Counter flow patterns. All are known to have disadvantages and advantages ("Comparison of Heat Exchanger Types", 2017), however the Counter Flow set up is known to be the most efficient as it requires the least Heat Exchanger surface area and has the high Log Mean Temperature (LMT) drop (Bengtson, 2010). Generally, it is accepted that this configuration is the most accepted for efficiency improvement despite its disadvantages (Shah et al, 2012).

Control parameters that run a Heat Exchange system also have an effect on the efficiency of operation (Shah et al, 2012). This depends on the type of Heat Exchanger used, for example a water to air Heat Exchanger would have an air flow rate, water flow rate and temperature controls (Thulukkanam, 2013). As mentioned in the previous section, varying flow rate will affect the capability of the exchanger to transfer heat, greater flows transfer more ("What Is a Heat Exchanger?", 2014). A research paper also finds that including vertical fins increases heat transfer area and by doing so the separation and reverse flow zones achieve redirection allowing more Heat Transfer (Thulukkanam, 2013) as previously mentioned using the vortices fins. However, Sadik et al publication concludes that in fact the fins need to be so thin that horizontal is preferred (Kakaç et al, 2013). The reason for this is that the spaces between the fins need to be large enough to allow high temperature fluid to reverse (Kakaç et al, 2013).

Multiple solutions are being implemented to better Heat Exchanger efficiencies. The analysis of many parameters and components can be done to improve them. This section concludes that the main objective to achieving improved efficiency is to maximum the Log Mean Temperature Difference as noted by Bengtsonin 2010. This is the key to having a Heat Exchanger that has enhanced performance and can be done with the above methods.

2.5 How successful are the solutions? (is it consistent, can it improved further, what are the limitations etc.

All the mentioned solutions for heat transfer enhancement are successful and used within the industry. In fact, there are companies designated to improving heat transfer in Heat Exchangers such as Calgavin Ltd("About CALGAVIN - CALGAVIN", 2017).The company states on their website how they can improve heat transfer(Higley, 2016):

- Using variable density tubes to make turbulators which help redirect fluid to improve flow pattern;
- Reducing fouling by lowering tube surface temperature; and
- Increasing the rate of condensation by method of surface drainage.

These are only three out of six noted methods used by the company. The fact that this company provides a service of Heat Exchanger performance enhancement shows the usefulness and success of this industry. However, these solution focus mainly on the flow pattern of the fluid and boundary layer control. Other mechanisms do deal with fouling, leakage, material selection, LMTD and so on but not as much. One interesting method mentioned is the pattern of Heat Exchanger flow and how there are three different types. However as each is known to have advantages and disadvantages ("Comparison of Heat Exchanger Types", 2017) a study could look into creating a hybrid flow pattern. These are already implemented in Shell and Tube Heat Exchangers (Bengtson, 2010) and could be looked into for other types of Heat Exchangers.

In Sadik's et al publication "Heat Transfer Enhancement of Heat Exchangers" in 2013, they conclude two main points after implementing vertical fins into the system (fins to dictate the flow behavior). As mentioned within the previous section, one point was that horizontal fins may be preferable rather than vertical as the space between the fins need to be large enough to allow high temperature fluid to increase (Sadik et al, 2013). A larger space between them

can mean either reducing the fins thickness or the number of fins used. A second important conclusion was that the heat transfer coefficients decrease by lowering fluid velocity due to the plates high conductivity (Sadik et al, 2013). Therefore, rather than fins, the use of adiabatic promoters can be implemented so there is no loss or increase in heat (Sadik et al, 2013). Other scientific papers agree that vorticity generating helps efficiency (Kasischke, 2002) and thermal boundary layer control improves heat transfer rate (Chormale et al, 2011).

Therefore, the solutions are working and implemented but can be further investigated. Some are limited to simply the material used to reduce loss of heat ("What Is a Heat Exchanger?", 2014), other methods involve the thermal boundary layer (Chormale et al, 2011).

2.6 Summary

The literature review confirms the important of Heat Exchanger use. They are widely used for a variety of applications and will be for some time. Improving their efficiency is a main target for the industry to enhance the performance and reduce losses. This saves time, money and mechanical effort. The problem relates to many factors surrounding Heat Exchangers from material choice, parameter flow rates, thermal boundary layer and others. There is interest in the work of Sadik et al work regarding the insertion of vertical fins. They note a horizontal fin could see improved thermal boundary layer performance. This shows a gap in the study that has been identified but yet to be confirmed.

Chapter 3

Methodology

3.1 Introduction

This section of the report will outline what the mathematical objective is to come up with a viable conclusion on Heat Exchanger performance. The necessary variable(s) are stated and mathematical equations presented with step by step sections. This is because many parameters rely on others and therefore it must know the basic variables to continue to the next. Note the parameters that are not to be calculated but noted before experiment as they too have an effect, for example the ambient pressure.

3.2 Theory

3.2.1 Overall Heat Transfer Coefficient (U)

The performance parameter will help determine Heat Exchanger configurations so that a differentiation can be done between them. The parameter that is being looked for is known as the Heat Transfer Coefficient (U) and is measured in W/m^2K . It provides a measure of how efficient a Heat Exchanger works (TD1007 Heat Exchanger – User guide). Essentially the overall Heat Transfer Coefficient is found by calculating the Rate of Heat Transfer ($\dot{Q}$), from one fluid at a given temperature, say T1, through a solid surface to another temperature T2; where T1 is generally larger than T2 ($T1 > T2$) (Roetzel et al, 2011). Therefore this will be the focus for comparing the various configurations of Heat Exchanger to see which is preferred.

$$U = \frac{\dot{Q}}{A \times LMTD}$$

Equation 1 - Overall Heat Coefficient

Where:

- $\dot{Q}$ = Rate of Heat Transfer (W)
- A = Heat Transfer Area (m^2).
- $LMTD$ = Log Mean Temperature Difference (K)

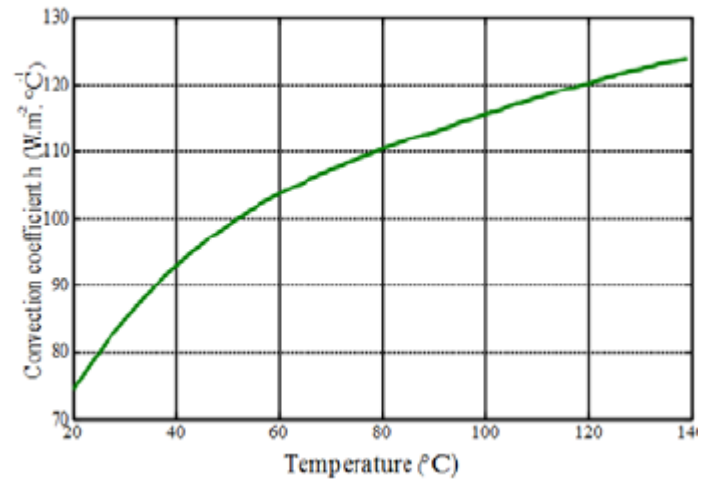
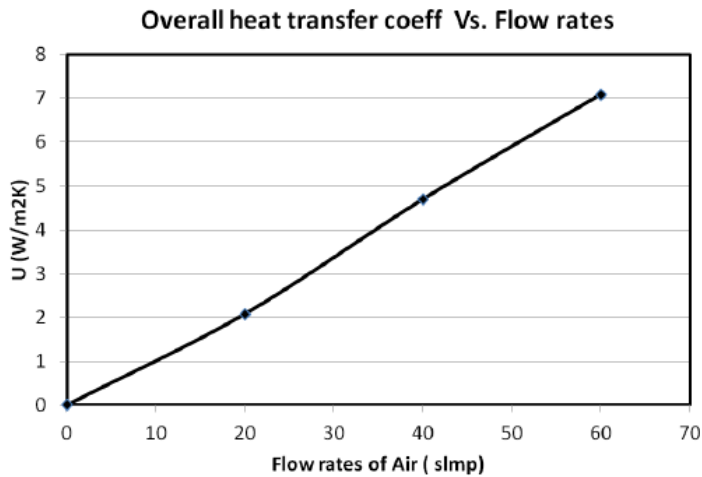


Figure 2 - Change of Heat Transfer Coefficient vs Temp/Flow rate (Anderson et al, 2013) (Talebi et al, 2014).

From Figure 1 it is seen that the overall Heat Transfer Coefficient increases with the flow rate of air and temperature. It is important to take this into account as a larger Heat Transfer Coefficient value indicates a better Heat Exchanger. Therefore, greater air flow rates and temperatures tend to improve performance. It is important to note that this is also dependent on the type of material used, the medium in which the heat is being exchanged amongst other factors.

3.2.2 Rate of Heat Transfer

This quantity must be found to determine the Heat Transfer Coefficient. Measured in Watts or Joules per second, the Rate of Heat Transfer is the power at which the heat is transferred per unit time (Isachenko et al, 1977). It is a function of mass flow rate, temperature difference and the specific heat capacity:

$$\dot{Q} = \dot{m} \times c_p \times \Delta T$$

Equation 2 - Rate of Heat Transfer

Where:

- $\dot{m}$ = Mass flow rate (kg/s)
- c_p = Specific heat capacity (J/kg/K).
- ΔT = Temperature Difference (K)

3.2.3 Specific Heat Capacity at Constant Pressure

The Specific Heat Capacity is the quantity of heat energy necessary to raise the temperature of 1kg of material by exactly a degree (1°C). It is a ratio between the heat energy and the difference or change in temperature shown below (Halliday et al, 2013):

$$c_p = \frac{Q}{\Delta T}$$

Equation 3 - Specific Heat Capacity

Note that in our case it is assumed isobaric process; a process where pressure is constant and therefore assumed pressure is not changing over a range of temperatures. Hence Q and not ΔQ is used in Equation 3.

When dealing with the Specific Heat Capacity of air, the value remains around 1005 J/kg/K usually. This is for conditions where atmospheric pressure is assumed and is typically the same for a range of Heat Exchanger temperatures (Halliday et al, 2013). For water, an equation providing an accurate answer can be used:

$$\frac{C_{pw}(at\ T^{\circ}C)}{C_{pw}(at\ 15^{\circ}C)} = 0.996185 + 0.0002874 \left(\frac{T + 100}{100} \right)^{5.26} + 0.011160 \times 10^{-0.036T}$$

Equation 4 - Specific Heat Capacity for water (TD1007 Heat Exchanger – User guide)

For this equation, the average temperature found should be used. Previous calculations have shown that the Specific Heat Capacity of water at 15°C is 4185.5 J/kg/K for reference (TD1007 Heat Exchanger – User guide). However an alternative method can be used also based on existing data for calculating Specific Heat Capacity. Figure 2 shows a relation between the Specific Heat Capacity and the temperature of water assuming pressure does not change. Interestingly, note that c_p is highly for temperatures close to freezing. An increase in temperature to about 35°C continuously decreases c_p until it increases again. Note that in order to achieve a high Overall Heat Transfer Coefficient value a high Rate of Heat Transfer is needed, and in order to achieve a high Rate of Heat Transfer a high Specific Heat Capacity is needed. Taking the average temperature once again, Figure 2 can be used to estimate our Specific Heat Capacity and check it using the formula provided.

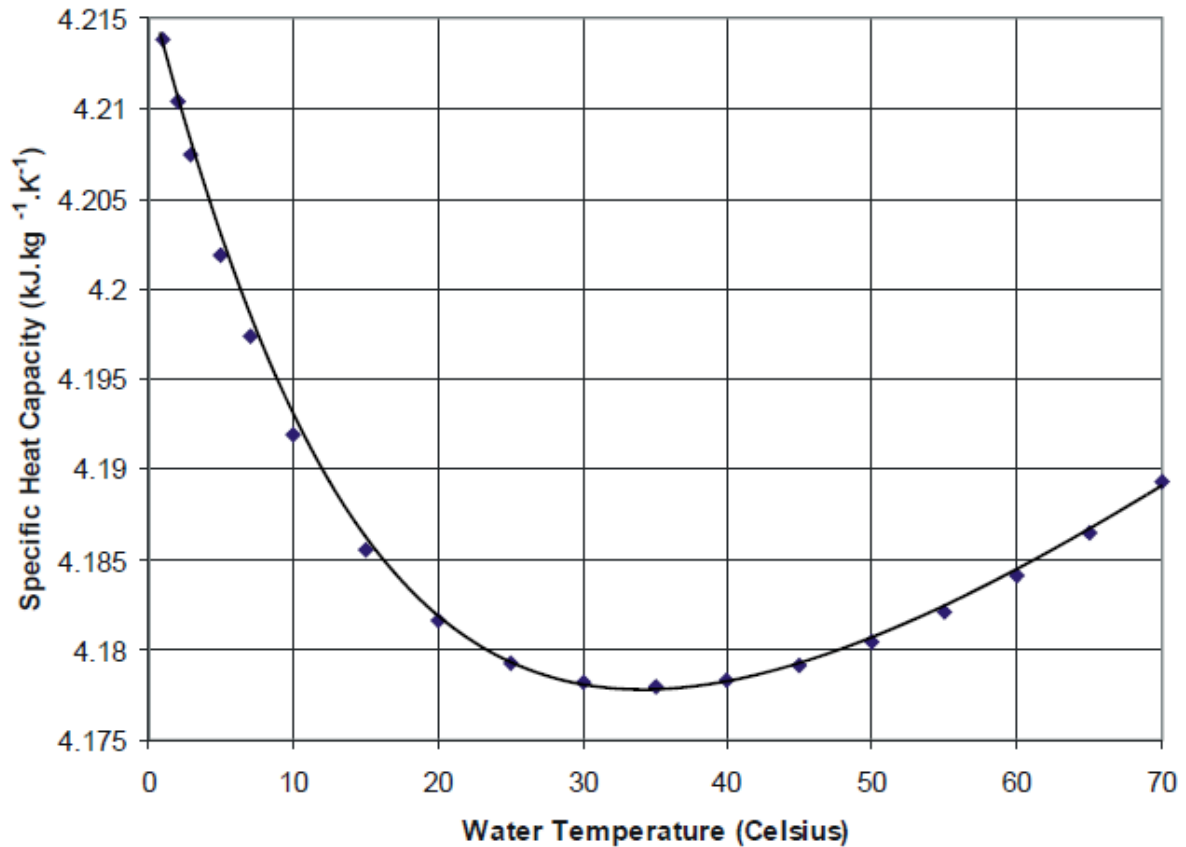


Figure 3 - Specific Heat Capacity vs Water Temperature for an Isobaric process(TD1007 Heat Exchanger – User guide)

3.2.4 Mass flow rate

For water, it is simply the volume of water flowing multiplied by the density of the water. Before doing this it is remembered that the volume flow for the TD1007 water to heat exchanger is set in Litres per minute (L/min). This is then to be converted into the equation so the units become kg/s for consistency. Equation is then presented:

$$\dot{m}_w = \text{volume flow}/60000 \times \rho_w$$

Equation 5 - Water mass flow rate(Gupta, 2002)

The volume flow entering the system can be selected by the user and will vary depending on test type and finally the density of water is known to be approximately 1 g/cm³ or 1000 kg/m³(Gupta, 2002). For air, the mass flow is dependent on the entrance hole (orifice). How much entering the system depends on the size of the orifice (area), the discharge coefficient and local conditions such as density. Information regarding the orifice area, discharge coefficient and pressure drop can be found in the user manual for the TD1007 manual.

$$\dot{m}_a = C_d \times A_0 \sqrt{\Delta p \times 2 \times \rho_a}$$

Equation 6 - Mass flow rate of air(TD1007 Heat Exchanger – User guide)

Equation 6 is then used to find the Mass Flow Rate for air entering the TD1007 Heat Exchanger. The density of air is dependent on the local conditions however for our case sea level atmospheric conditions are used where the density is known to be approximately 1.225 kg/m³(R. K. Bansal, 2005).

3.2.5 Heat Transfer Area

It is important to know the Heat Transfer Area to determine the Overall Heat Transfer Coefficient as known from Equation. The Heat Transfer Area has an effect on both the water power and amount of Heat Transferred. It varies depending on the type of configuration used, for example with or without fins, standard 32 tube Heat Exchanger or 16 tube Heat exchangers. When looking at Equation, increasing the area will decrease the Overall Heat Transfer Coefficient which is not desired. However, making the area as small as possible is also not practical.

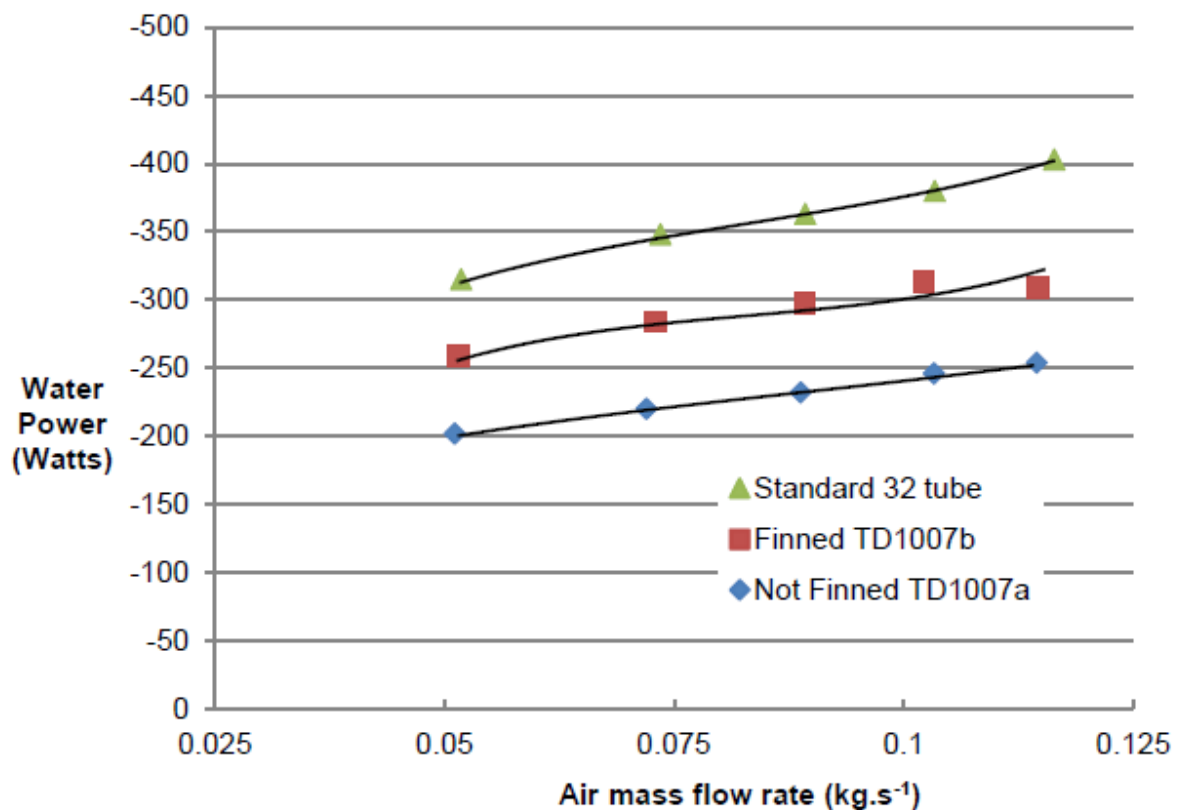


Figure 4 - Water power vs Air mass flow rate(TD1007 Heat Exchanger – User guide)

Figure 3 shows three different Heat Exchanger configurations and their performance in terms of water power. Seen from the Non-Finned configuration that it exchanges almost half the amount compared with the standard Heat Exchanger Configuration whereas the finned one exchanges more (TD1007 Heat Exchanger – User guide). Note that the non-finned configuration has the least area. Therefore, it can be said that although a small area is preferred to have high Heat Transfer Coefficient, there is a sacrifice in the power of the water as a result. Therefore, there must be a trade-off and select one that is not too large nor too small that provides good water power.

This value does not need to be calculated and can be found within the TD1007 Heat Exchanger User Guide. A table with the different Heat Transfer areas depending on required configuration is provided and can be found on page 16.

Table 1 - Heat exchanger configuration areas (TD1007 Heat Exchanger – User guide).

Heat Exchanger	Details
Standard 32 Tube Heat Exchanger	Nett Dimensions: 130 mm wide x 280 mm front to back x 210 mm high and 3.2 kg 2 x Tube bundle of 16 copper tubes. Mean Heat Transfer Area = $2 \times 0.0779 = 0.1558 \text{ m}^2$
Optional 16 Tube Heat Exchanger (TD1007a)	Nett Dimensions: 130 mm wide x 280 mm front to back x 210 mm high and 3 kg 1 x Tube bundle of 16 copper tubes. Mean Heat Transfer Area = 0.0779 m^2
Optional 16 Tube Finned Heat Exchanger (TD1007b)	Nett Dimensions: 130 mm wide x 280 mm front to back x 210 mm high and 3 kg 1 x Tube bundle of 16 copper tubes and 7 x vertical fins. Mean Heat Transfer Area = 0.1558 m^2

3.2.6 Log Mean Temperature Difference (LMTD)

The Log Mean Temperature difference is simply the driving force measured that provides the heat transfer (Thulukkanam, 2013). It is the logarithmic average between the hot and cold fluid temperatures in the Heat Exchanger and is designed to inform about how much drive force the Heat Exchanger is working at (TD1007 Heat Exchanger – User guide) (Thulukkanam, 2013). It is quantified using the equation:

$$LMTD = \frac{(T_{WX} - T_{AX}) - (T_{WY} - T_{AY})}{\ln \left(\frac{T_{WX} - T_{AX}}{T_{WY} - T_{AY}} \right)}$$

Equation 7 - Log Mean Temperature Difference (Cen et al, 2009)

Where the subscript 'w' denotes the temperature of water and 'a' denotes the temperature for air ('x' and 'y' simply referring to stages of the Heat Exchanger). These temperature values will be available as raw data, provided by the TD1007 water to air Heat Exchanger. The LMTD is measured in Kelvin or Degrees Celsius.

3.2.7 Energy Balance Coefficient

It is known that in an ideal Heat Exchanger system, energy should not be transferred between the system and its surroundings, i.e. hot air being cooled due to colder surroundings. However, this does occur and there is what is known as a Real Heat Exchanger where occurrence is acknowledged. It has to be accounted for and so there is what is known as the Energy Balance Coefficient. It provides a value that best describes the real system against ideal. Essentially, it is the value of the energy absorbed and energy emitted, it is found as the ratio between heat energy transfer for water and air:

$$C_{EB} = \frac{\dot{Q}_a}{\dot{Q}_w}$$

Equation 8 - Energy balance

3.2.8 Temperature Efficiency and the Mean

It can also be seen how efficient the system performed thermally by calculating the Temperature Efficiencies for both hot and cold circuits. Simply by dividing the maximum and minimum:

$$\eta_w = \frac{T_{w1} - T_{w2}}{T_{w1} - T_{a1}} \times 100 \quad \eta_a = \frac{T_{a2} - T_{a1}}{T_{w1} - T_{a1}} \times 100$$

Equation 9 - Temperature Efficiencies

The average of the two efficiencies gives the mean average efficiency $\bar{\eta}$.

3.3 Choice of Apparatus

The use of a physical Heat Exchanger is vital to this investigation so that carrying out experiments and test the theory for research purpose is done. Without the use of a Heat Exchanger it would only be able to predict and guide other researches regarding Heat Exchanger uses. However, with the use of one it is better to guide other researches by eliminating any issues that may occur and to present results that are not useful. Therefore, directing other engineers when coming across this project again.

The Heat Exchanger currently available for use is known as the water to air TD1007 Heat Exchanger and can be experimented on. This is the selected equipment for the investigation and will focus largely around it. Previous experiments have been done using this Heat Exchanger and so a basic knowledge is helpful for this project.

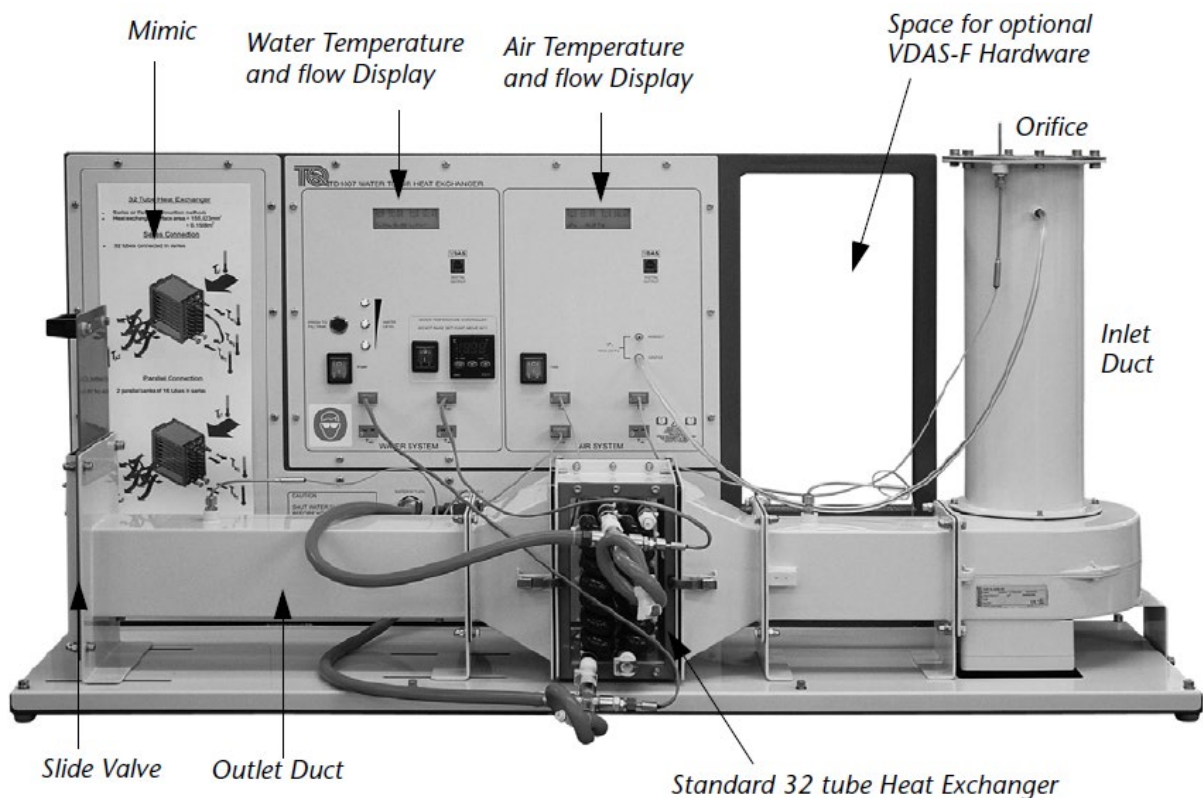


Figure 5 - TD1007 water to air Heat Exchanger(TD1007 Heat Exchanger – User guide)

Figure 5 displays the TD1007 Heat exchanger with the components for operation. This was taken from the user guide for this Heat Exchanger and was provided with the machine. The manual and user guide will be heavily used to correctly understand and operate the Heat Exchanger.

This bench top Heat Exchanger user guide will provide information important to the success of this investigation. Its primary function is to give the user an understanding of the uses and performance expected from typical water to air Heat Exchanger. Figure 5as mentioned, outlines each component for example helping to locate them. Note that the Heat Exchanger is mentioned as being the standard 32 tube in Figure 5. This is not the case for our experiment and will vary, Figure 5 is for example purposes only. The below figure displays the actual TD1007 water to heat exchanger in the lab.



Figure 6 - Benchtop TD1007 water to air Heat Exchanger

3.4 How does it work?

As known from the literature review, the prime objective of a heat exchanger is to convert heat between two mediums, but how does the TD1007 Heat Exchanger do so? Remembering this Heat Exchanger is the water to air Heat Exchanger and works with the use of tubes containing water (hot or cold). Figure 7 displays the inside workings of this Heat Exchanger and identity of the components can be done. Airflow enters through the orifice in the top right corner, before being accelerated with the use of a fan towards the Heat Exchanger itself.

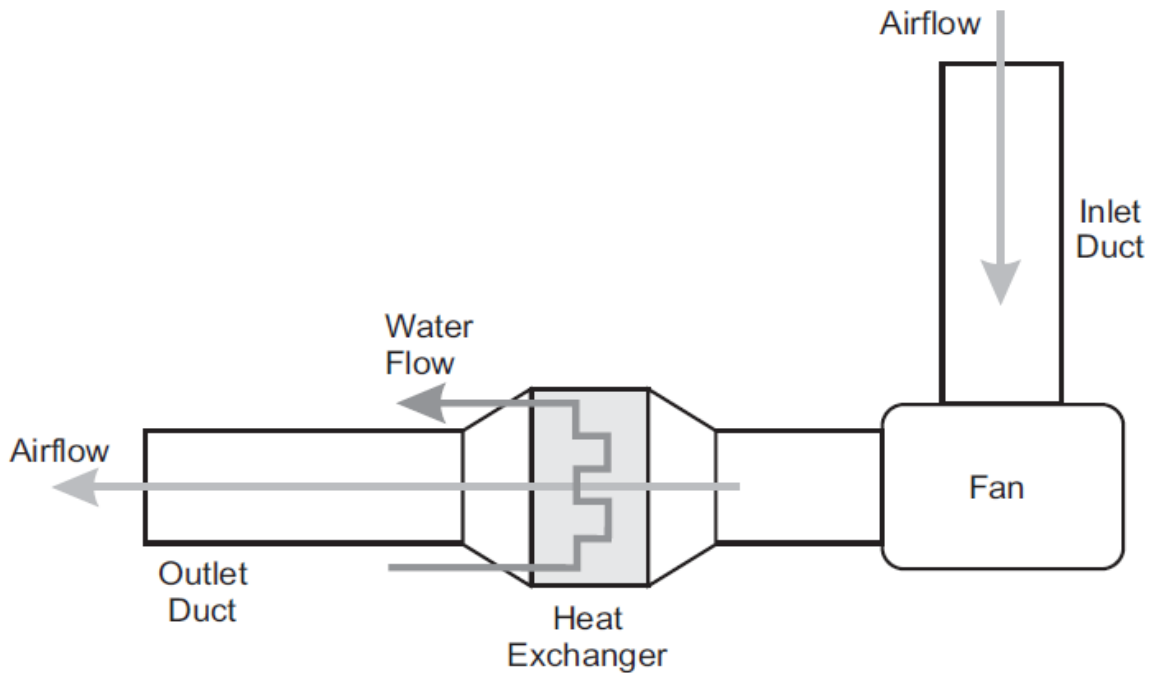


Figure 7 - TD1007 HX diagram(TD1007 Heat Exchanger – User guide)

This is where the tubes are located and have water flowing through them, for example cold running water. The air then passes through the Heat Exchanger and the physics begins to take place. Continuing on after the Heat Exchanger to the outlet duct where it is then used for whatever reason. It is a continuous open circuit as the air that is released is not then returned back into the inlet duct directly. As the air coming in is from atmospheric and the outlet duct releases to atmospheric, it is an open circuit Heat Exchanger not a closed one.

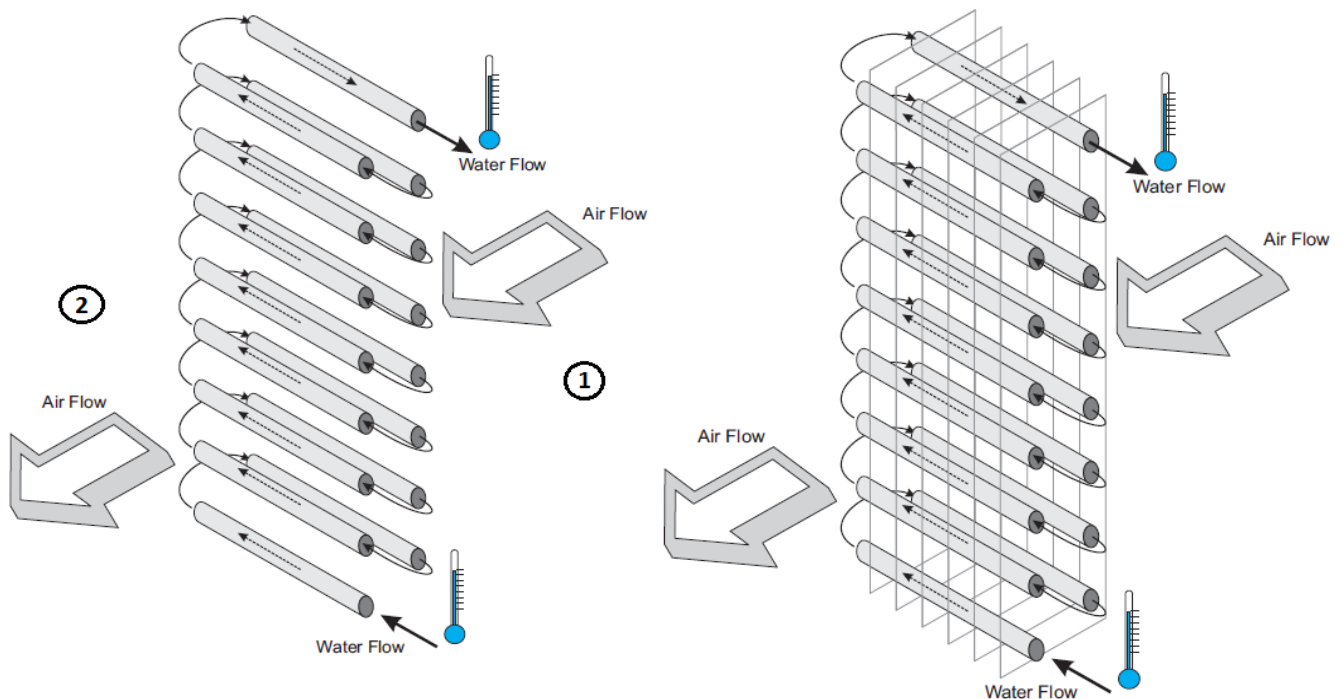


Figure 8 - 16 Tube Heat Exchanger(TD1007 Heat Exchanger – User guide)

Figure 8 displays a typical 16 Tube Heat Exchanger layout (left) where it can be seen the flow properties 1 and 2 in the direction of air flow. Where $T_2 > T_1$ depending on the requirement from the Heat Exchanger. The diagram to the right shows the same layout but with an inserted “vertical fin”. As explained in the previous section, increasing the Heat Transfer area improves performance.

The tubes can also be connected in either a parallel or series connection, this also affects the performance of the Heat Exchanger as described previously. A diagram displaying the connections is shown in Figure 9. This is dependent on how many sets of 16 tubes are to be used, in this example 32 tubes are used.

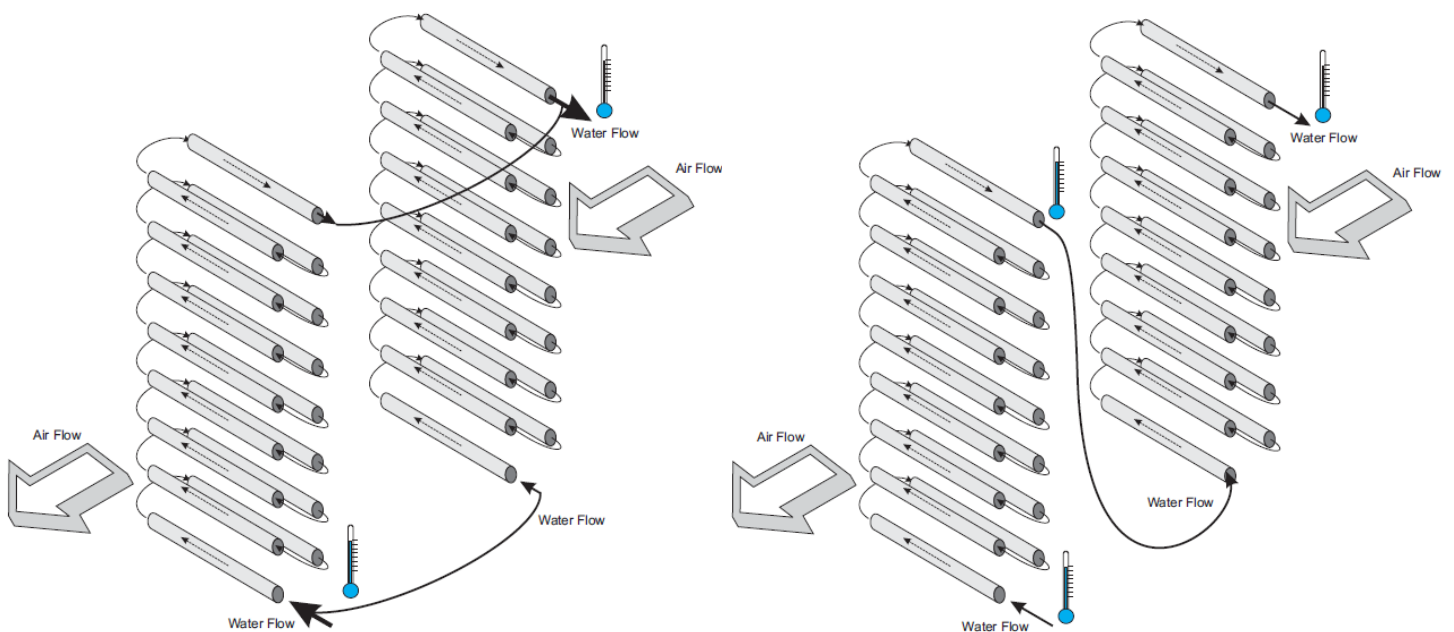


Figure 9 - 32 Tube Series vs Parallel HX(TD1007 Heat Exchanger – User guide)

The objective of the report is not to identify which connection type is best and why but to focus on air variation, water flow variation and the heat transfer area (use of fins). However, the best performance will be mentioned and noted for further research and investigation.

Figures 10 to 13 display the actual 16 tube and 32 tube configuration used in the lab, how they are connected to the bench top Heat Exchanger itself and how the tube was connected for the water flow.



Figure 10 - Side by side 16 tube and 32 tube configuration



Figure 11 - 32 tube connection

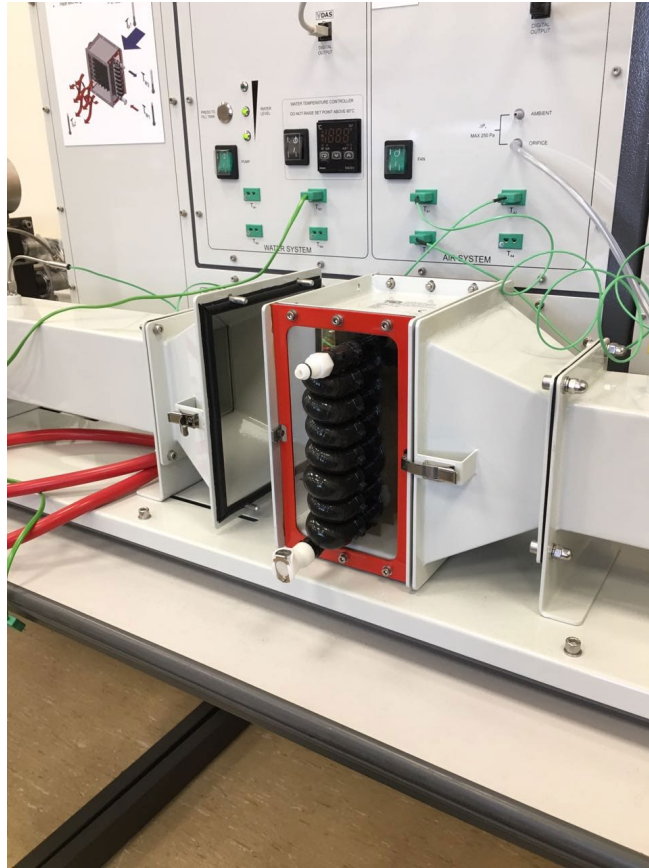


Figure 12 - 16 tube configuration connection

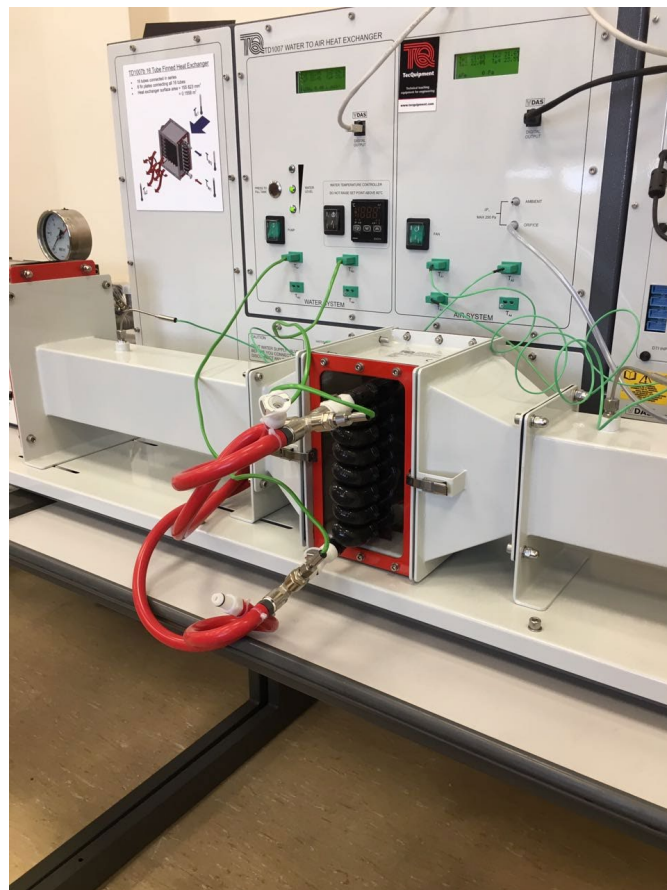


Figure 13 - Pipe connection to Heat Exchanger

3.5 Procedure

The following steps were designed to be carried out in order to obtain the data from the Heat Exchanger is done as follows:

1. Trying and doing all the tests in one sitting as a change in ambient temperature will have a large affect - this will ensure more accurate findings. (Take note of the ambient temperature before each Heat exchanger test).
2. The fan setting, heater and pump need to be consistent for all configurations for the same reason. (Take note of all these values before each Heat exchanger test).
3. Trying and getting someone to help you carry out the experiment. This again is for consistency with results. One person to control the machine and the other to note the results.
4. Take the readings more than once – preferably three times for each variable. Waiting roughly 15-20 seconds between each reading.
5. When turned on, give the machine a few minutes (5-10 minutes) to reach optimum levels before any recording.
6. Note down the data readings according to the experiment being conducted.
7. Switch of the heater, set air and water flow to maximum and allow the fan to cool the heat exchanger for roughly 5 minutes before switching off.
8. Change the Heat Exchanger according to the necessary experiment being conducted.
9. Repeat step 5 followed by step 6 and 7 etc.

Chapter 4

Results and Analysis

4.1 Introduction

This section will provide tabulated data and graphical figures of the results. It will help understand and analyze the results found as well as comparing them against each other. First however, the raw data must be defined that was used throughout the experiment. Note: fixed data listed only differ when that parameter is being varied for an experiment (i.e. heater temperature of 60°C is true for varying water and air flow experiments but not for temperature varying experiments), they are tabulated below:

Table 2 - Raw experimental data

Raw Data	
Heater Temperature	60°C
Water flow	2.5 L/min
Orifice pressure drop	250 Pa
Orifice coefficient of discharge	0.6
Orifice diameter	100.11mm
Orifice area	0.008m
Air specific heat capacity	1005 J/kg.k
Heat transfer area (32 tube)	0.1558m
Heat transfer area (16 tube)	0.0779m
Specific gas constant	287 J/kg.K
Density of water	1000 kg/m ³

This raw data was used throughout the experimental process to calculate the actual data whether directly or not, for example the use of water density to calculate mass flow. The sample calculations on how it was gained can be found within the Appendices, page 45. The tabulated results are presented:

4.2 Experiment 1a – 32 Tube Configuration – Varying water flow

Table 3 - Experiment 1a using a 32 Tube configuration

Hot Flow (L/min)	T_{w1} (°C)	T_{w2} (°C)	ΔT_w (°C)	$\bar{T}_w$ (°C)	T_{w3} (°C)	T_{a1} (°C)	T_{a2} (°C)	ΔT_a (°C)	$\bar{T}_a$ (°C)	T_{a3} (°C)	$\dot{m}_w$ $\left(\frac{kg}{s}\right)$	$\dot{m}_a$ $\left(\frac{kg}{s}\right)$	ρ_w $\left(\frac{kg}{m^3}\right)$	ρ_a $\left(\frac{kg}{m^3}\right)$
1.5	60.2	53.8	-6.4	57.0	28.7	22.3	27.7	5.4	25	21	0.025	0.116	985	1.18
2	60.6	55.8	-4.8	58.2	31.1	22.7	28.4	5.7	25.55	21.5	0.033	0.116	984.5	1.18
2.5	60.9	57	-3.9	58.9	32	23.1	28.9	5.8	26	21	0.041	0.116	984	1.18
2.7	61	57.3	-3.7	59.1	33	23.5	29.3	5.8	26.4	23.1	0.045	0.116	984	1.18
2.8	61.1	57.5	-3.6	59.3	33.2	23.5	29.4	5.9	26.45	21.3	0.046	0.116	984	1.18

	η_w (%)	η_a (%)	$\bar{\eta}$ (%)	C_{pw} $\left(\frac{J}{kg.K}\right)$	C_{pa} $\left(\frac{J}{kg.K}\right)$	Q_w (W)	Q_a (W)	C_{EB}	$LMTD$ (°C)	$\frac{U}{m^2K}$	
	16.9	14.2	15.57	4.183	1005	-0.669	632.74	-945.4	31.63	-0.136	
	12.7	15.0	13.85	4.184	1005	-0.669	667.89	-997.7	32.37	-0.133	
	10.3	15.3	12.83	4.184	1005	-0.680	679.61	-999.6	32.71	-0.133	
	9.9	15.5	12.67	4.184	1005	-0.697	679.61	-975.6	32.52	-0.137	
	9.6	15.7	12.63	4.184	1005	-0.703	691.33	-983.5	32.62	-0.138	

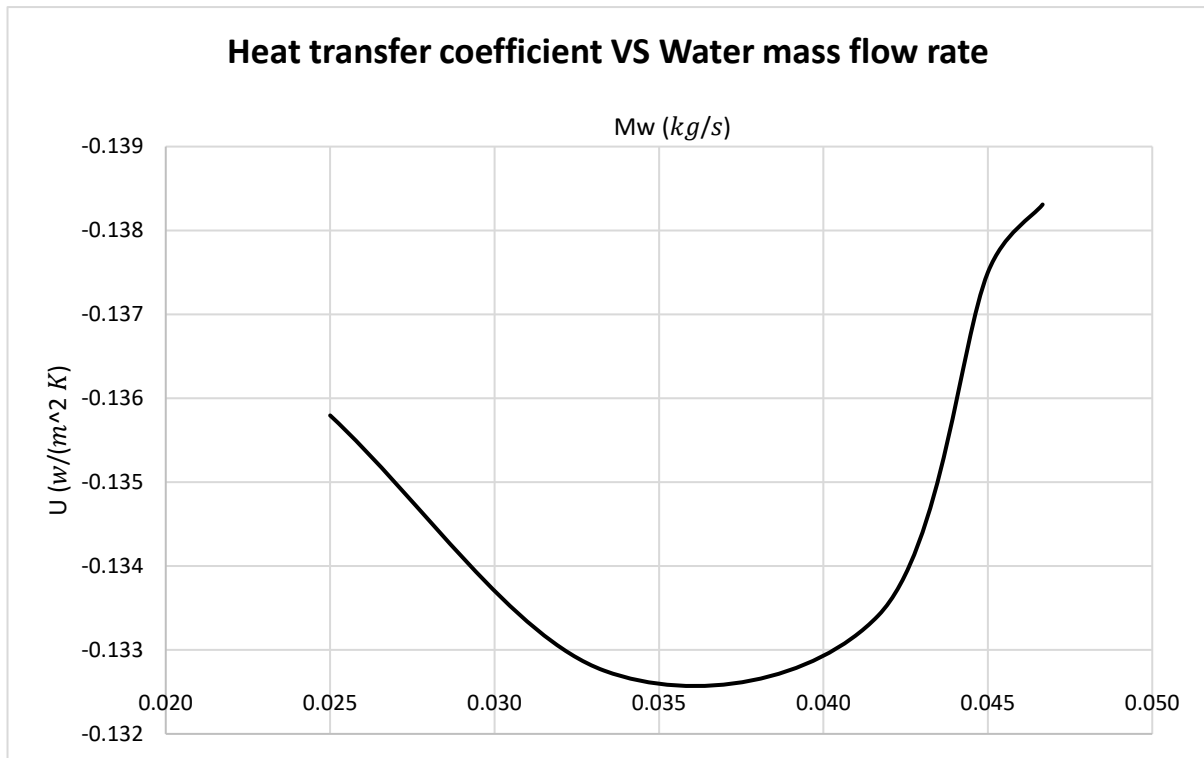


Figure 14 - Experiment 1a (U vs Mw)

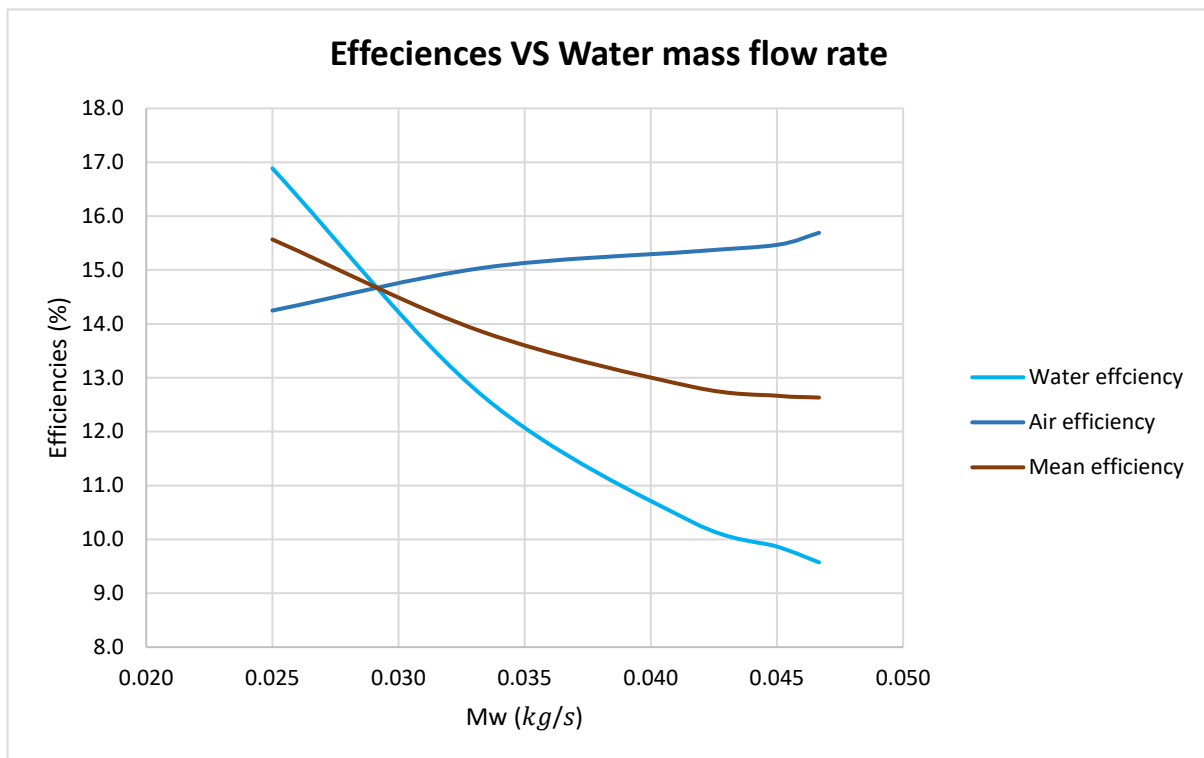


Figure 15 – Experiment 1a (Efficiencies vs Mw)

4.3 Experiment 1b – 32 Tube Configuration – Varying air flow

Table 4 - Experiment 1b using 32 Tube configuration

Δp (Pa)	T_{w1} (°C)	T_{w2} (°C)	ΔT_w (°C)	$\bar{T}_w$ (°C)	T_{w3} (°C)	T_{a1} (°C)	T_{a2} (°C)	ΔT_a (°C)	$\bar{T}_a$ (°C)	T_{a3} (°C)	$\dot{m}_w$ ($\frac{kg}{s}$)	$\dot{m}_a$ ($\frac{kg}{s}$)	ρ_w ($\frac{kg}{m^3}$)	ρ_a ($\frac{kg}{m^3}$)
220	61.2	57.4	-3.8	59.30	34.3	24.2	30	5.8	27.1	23.7	0.042	0.109	985	1.18
230	61.2	57.3	-3.9	59.25	34.1	24	29.8	5.8	26.9	23.6	0.042	0.112	984.5	1.18
240	61.1	57.2	-3.9	59.15	34	23.9	29.6	5.7	26.75	23.4	0.042	0.114	984	1.18
250	61.1	57.1	-4	59.10	33.7	23.8	29.5	5.7	26.65	23.4	0.042	0.117	984	1.18
η_w (%)		η_a (%)		$\bar{\eta}$ (%)	C_{pw} ($\frac{J}{kg.K}$)	C_{pa} ($\frac{J}{kg.K}$)	Q_w (W)	Q_a (W)	C_{EB}	$LMTD$ (°C)	U_w ($\frac{W}{m^2.K}$)			
10.27		15.68		12.97	4.183	1005	-0.662	637.53	-962.59	31.96	-0.133			
10.48		15.59		13.04	4.184	1005	-0.680	651.86	-958.76	32.11	-0.136			
10.48		15.32		12.90	4.184	1005	-0.680	654.40	-962.50	32.16	-0.136			
10.72		15.28		13.00	4.184	1005	-0.697	667.89	-957.78	32.21	-0.139			

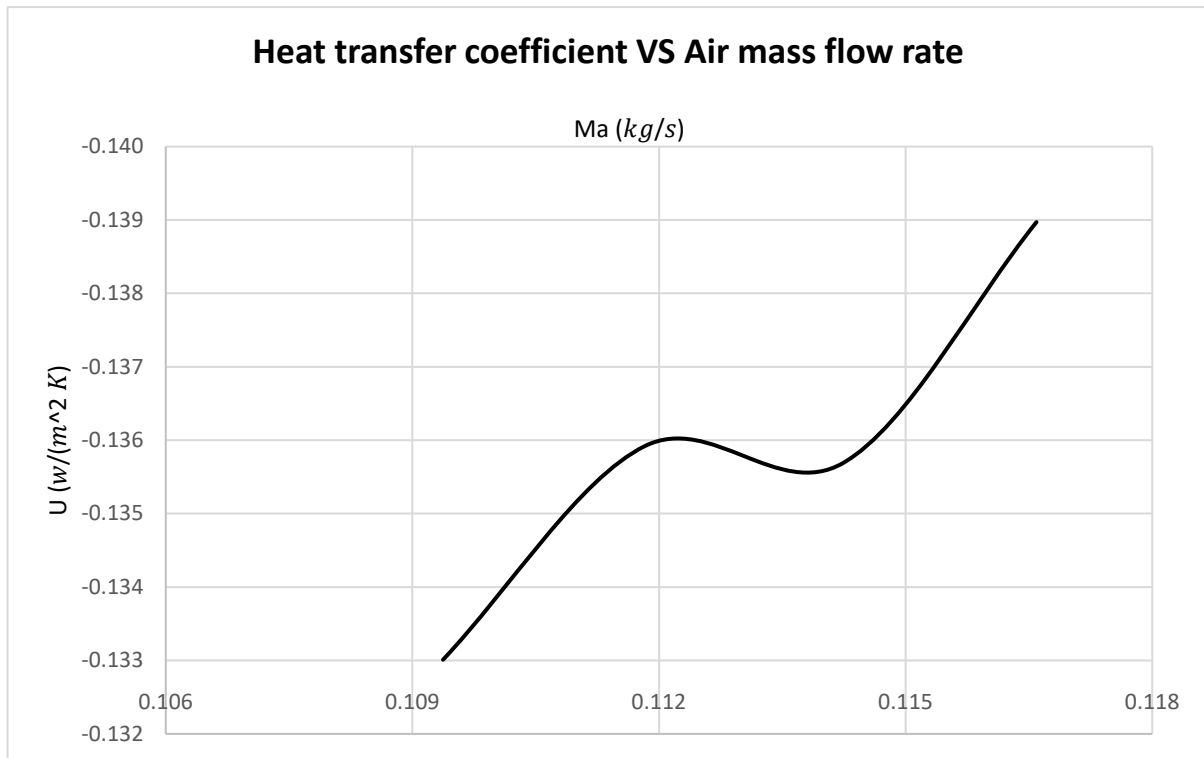


Figure 16 - Experiment 1b (U vs Ma)

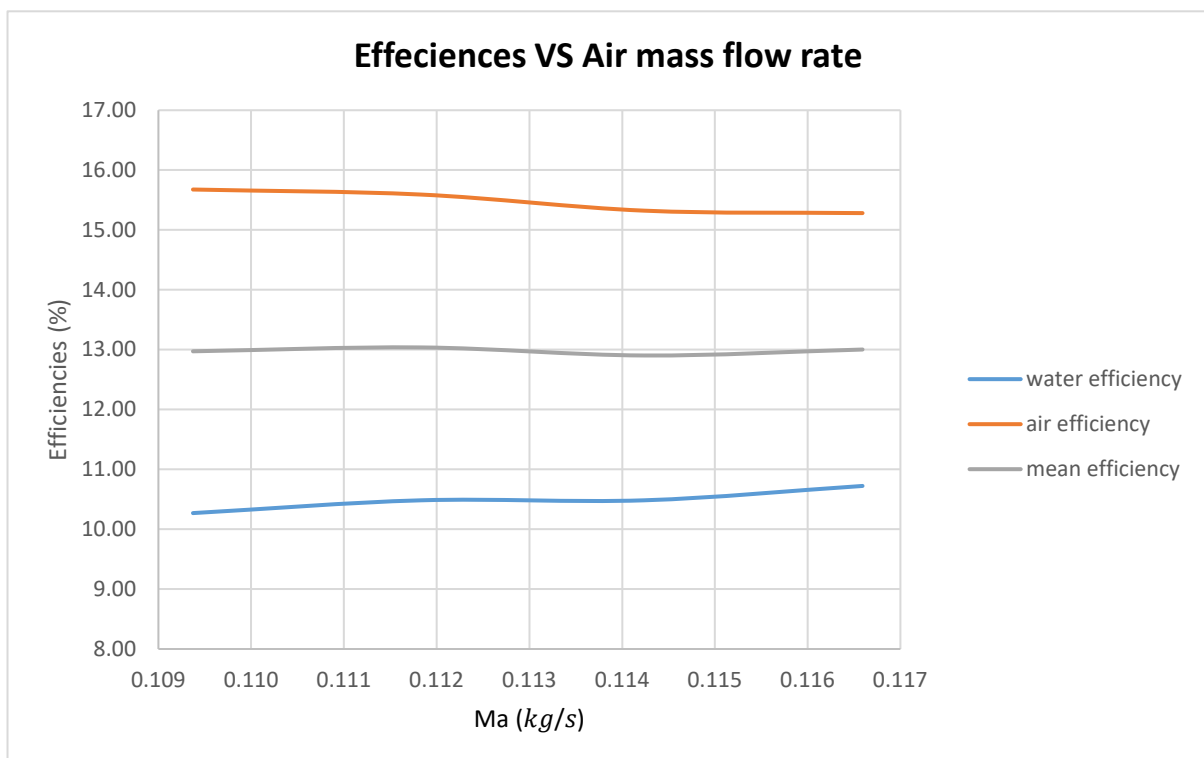


Figure 17 - Experiment 1b (Efficiencies vs Ma)

4.4 Experiment 1c – 32 Tube Configuration – Varying HX Temperature

Table 5 - Experiment 1c using 32 tube configuration

Heater Temperature (°C)	T_{w1} (°C)	T_{w2} (°C)	ΔT_w (°C)	$\bar{T}_w$ (°C)	T_{w3} (°C)	T_{a1} (°C)	T_{a2} (°C)	ΔT_a (°C)	$\bar{T}_a$ (°C)	T_{a3} (°C)	$\dot{m}_w$ $\left(\frac{kg}{s}\right)$	$\dot{m}_a$ $\left(\frac{kg}{s}\right)$	ρ_w $\left(\frac{kg}{m^3}\right)$	ρ_a $\left(\frac{kg}{m^3}\right)$
30	31.5	30.8	-0.7	31.15	26.6	23.7	25	1.3	24.35	23.1	0.033	0.104	995	1.18
40	41.4	39.3	-2.1	40.35	28.5	23.9	26.7	2.8	25.3	23.3	0.033	0.104	993	1.18
50	51.2	48	-3.2	49.60	31.2	24.5	28.7	4.2	26.6	24	0.033	0.104	988	1.18
60	61	56.5	-4.5	58.75	34.6	24.3	30	5.7	27.15	23.6	0.033	0.104	984	1.18
η_w (%)		η_a (%)	$\bar{\eta}$ (%)	C_{pw} $\left(\frac{J}{kg.K}\right)$	C_{pa} $\left(\frac{J}{kg.K}\right)$	Q_w (W)	Q_a (W)	C_{EB}	$LMTD$ (°C)	U $\left(\frac{W}{m^2.K}\right)$				
8.97		16.67	12.82	4.176	1005	-0.097	136.25	-1398.3	6.75	-0.093				
12.00		16.00	14.00	4.176	1005	-0.292	293.45	-1003.9	14.92	-0.126				
11.99		15.73	13.86	4.181	1005	-0.446	440.18	-987.0	22.80	-0.126				
12.26		15.53	13.90	4.184	1005	-0.628	597.38	-951.9	31.32	-0.129				

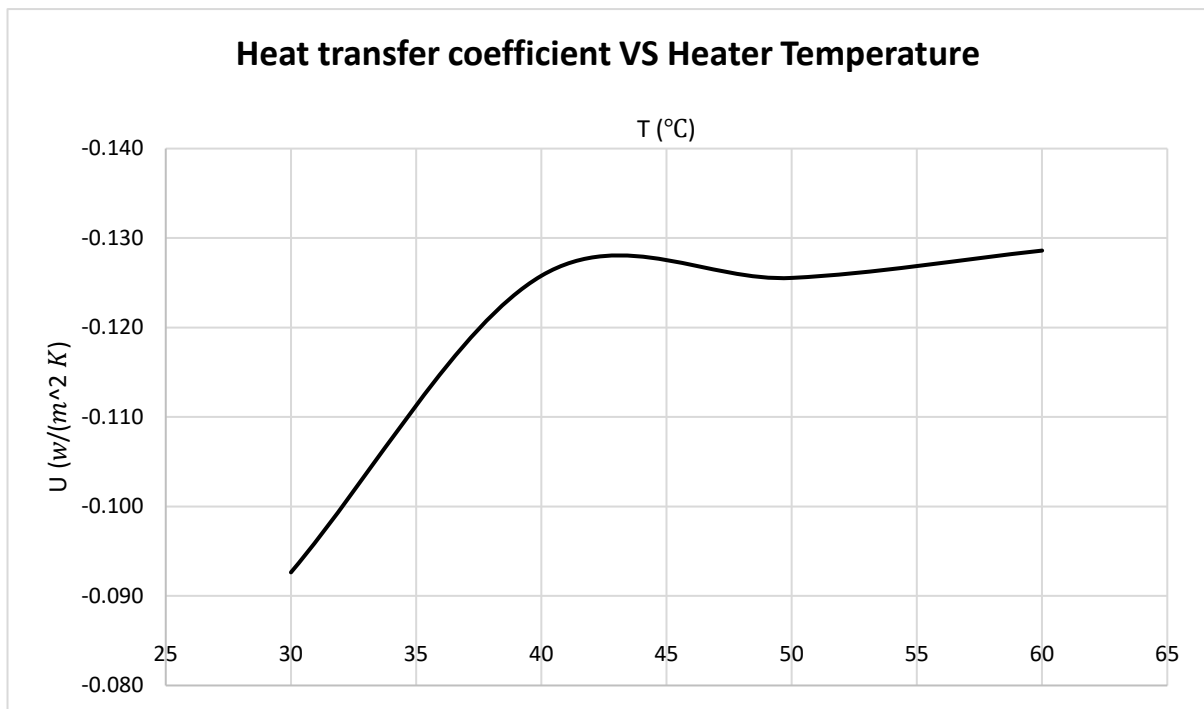


Figure 18 - Experiment 1c (U vs T)

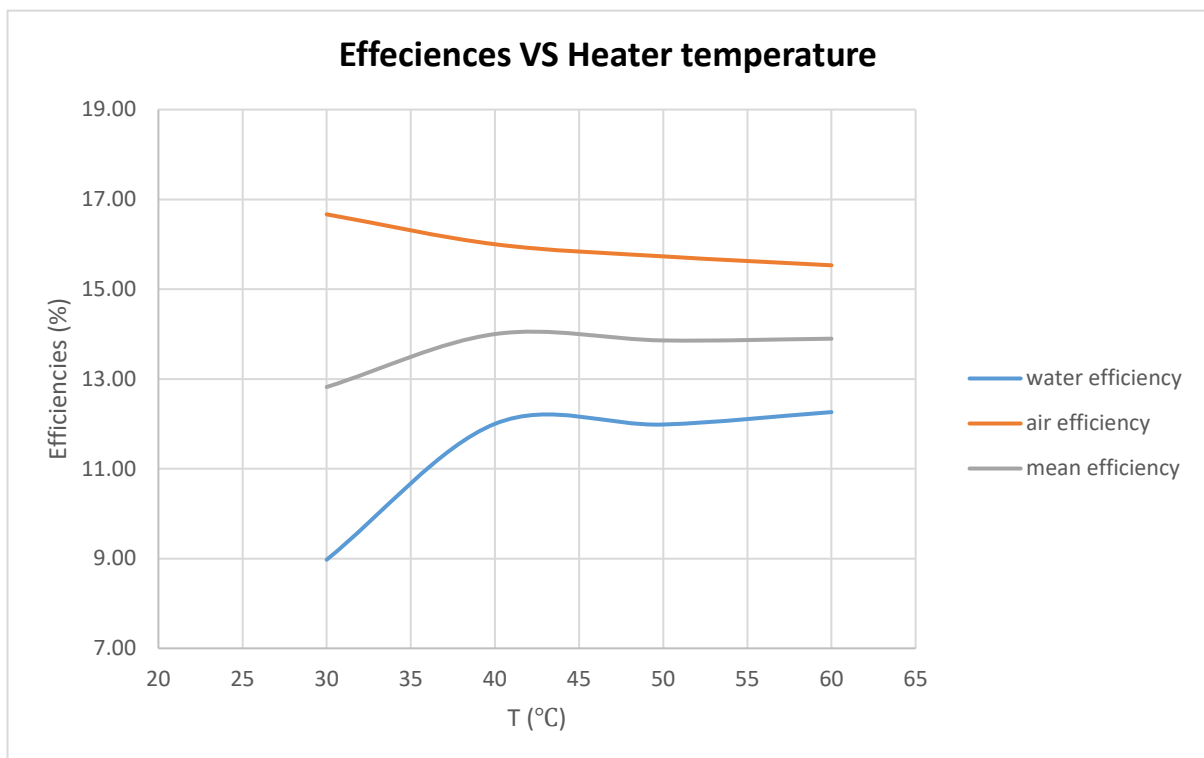


Figure 19 - Experiment 1c (Efficiencies vs T)

4.5 Experiment 2a – 16 Tube Configuration – Varying water flow

Table 6 - Experiment 2a using 16 tube configuration

Hot Flow (L/min)	T_{w1} (°C)	T_{w2} (°C)	ΔT_w (°C)	$\bar{T}_w$ (°C)	T_{w3} (°C)	T_{a1} (°C)	T_{a2} (°C)	ΔT_a (°C)	$\bar{T}_a$ (°C)	T_{a3} (°C)	$\dot{m}_w$ $\left(\frac{kg}{s}\right)$	$\dot{m}_a$ $\left(\frac{kg}{s}\right)$	ρ_w $\left(\frac{kg}{m^3}\right)$	ρ_a $\left(\frac{kg}{m^3}\right)$
1.5	60.7	56.1	-4.6	58.40	31.2	24	28.3	4.3	26.15	23.6	0.0250	0.1166	985	1.18
2	61.1	57.5	-3.6	59.30	33.2	25	29.3	4.3	27.15	24.6	0.0333	0.1166	984	1.18
2.5	61	58.3	-2.7	59.65	34.2	25.2	29.6	4.4	27.4	24.8	0.0417	0.1166	984	1.18
2.7	61.3	58.8	-2.5	60.05	34.7	25.9	30.2	4.3	28.05	25.4	0.0450	0.1166	983	1.18
	η_w (%)	η_a (%)	$\bar{\eta}$ (%)	C_{pw} $\left(\frac{J}{kg.K}\right)$	C_{pa} $\left(\frac{J}{kg.K}\right)$	Q_w (W)	Q_a (W)	C_{EB}	$LMTD$ (°C)	$\frac{U}{m^2K}$				
	12.53	11.72	12.13	4.183	1005	-0.481	503.85	-1047.4	32.04	-0.193				
	9.97	11.91	10.94	4.184	1005	-0.502	503.85	-1003.5	31.99	-0.201				
	7.54	12.29	9.92	4.184	1005	-0.471	515.57	-1095.3	32.12	-0.188				
	7.06	12.15	9.60	4.185	1005	-0.471	503.85	-1070.2	31.88	-0.190				

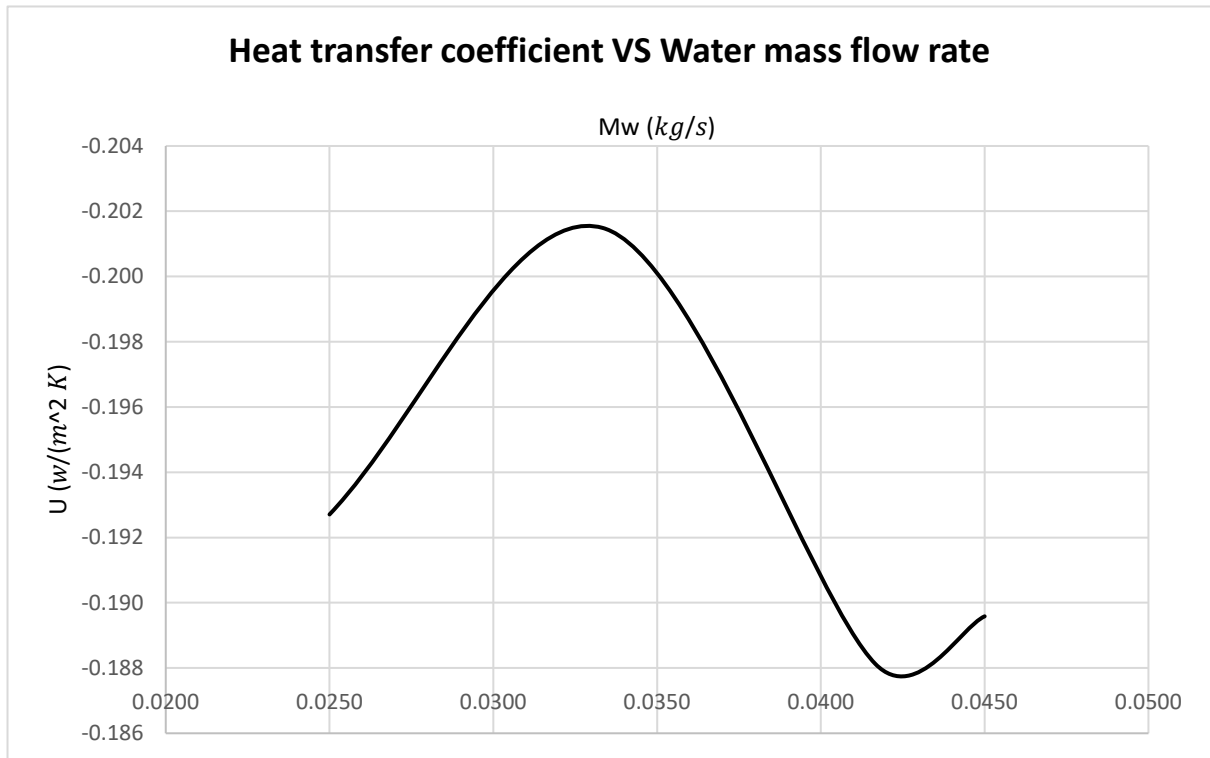


Figure 20 - Experiment 2a (U vs M_w)

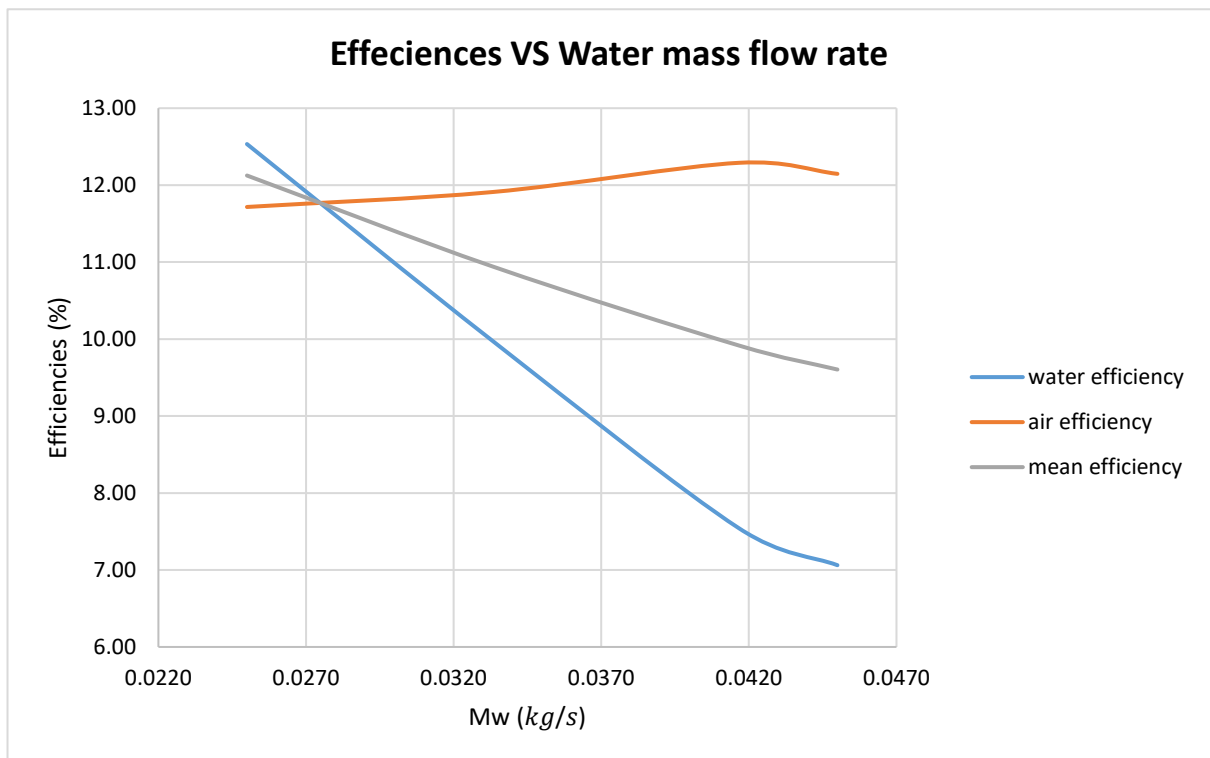


Figure 21 - Experiment 2a (Efficiencies vs M_w)

4.6 Experiment 2b – 16 Tube Configuration – Varying air flow

Table 7 - Experiment 2b using 16 tube configuration

Δp (Pa)	T_{w1} (°C)	T_{w2} (°C)	ΔT_w (°C)	$\bar{T}_w$ (°C)	T_{w3} (°C)	T_{a1} (°C)	T_{a2} (°C)	ΔT_a (°C)	$\bar{T}_a$ (°C)	T_{a3} (°C)	$\dot{m}_w$ ($\frac{kg}{s}$)	$\dot{m}_a$ ($\frac{kg}{s}$)	ρ_w ($\frac{kg}{m^3}$)	ρ_a ($\frac{kg}{m^3}$)
220	61.2	58.6	-2.6	59.90	35.3	26.4	30.8	4.4	28.6	25.9	0.042	0.109	985	1.18
230	61.1	58.5	-2.6	59.80	35.6	26.5	30.9	4.4	28.7	26.1	0.042	0.112	984.5	1.18
240	61.2	58.6	-2.6	59.90	35.8	26.7	31	4.3	28.85	26.4	0.042	0.114	984	1.18
250	61.3	58.6	-2.7	59.95	35.9	26.8	31	4.2	28.9	26.4	0.042	0.117	984	1.18
η_w (%)		η_a (%)		$\bar{\eta}$ (%)	C_{pw} ($\frac{J}{kg.K}$)	C_{pa} ($\frac{J}{kg.K}$)	Q_w (W)	Q_a (W)	C_{EB}	$LMTD$ (°C)	U_w ($\frac{W}{m^2.K}$)			
7.47		12.64		10.1	4.18	1005	-0.453	483.65	-1067.3	31.17	-0.187			
7.51		12.72		10.1	4.18	1005	-0.453	494.52	-1091.0	30.97	-0.188			
7.54		12.46		10	4.18	1005	-0.453	493.67	-1089.1	30.92	-0.188			
7.83		12.17		10	4.18	1005	-0.471	492.13	-1045.5	30.92	-0.195			

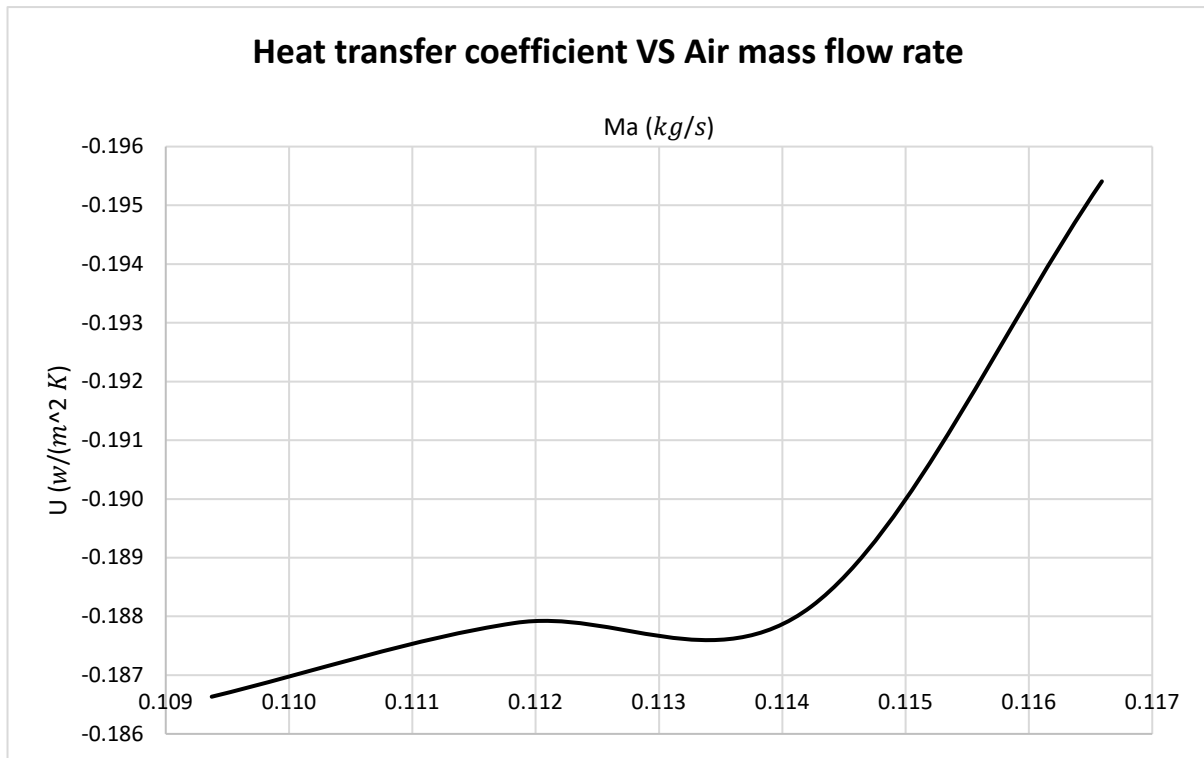


Figure 22 - Experiment 2b (U vs Ma)

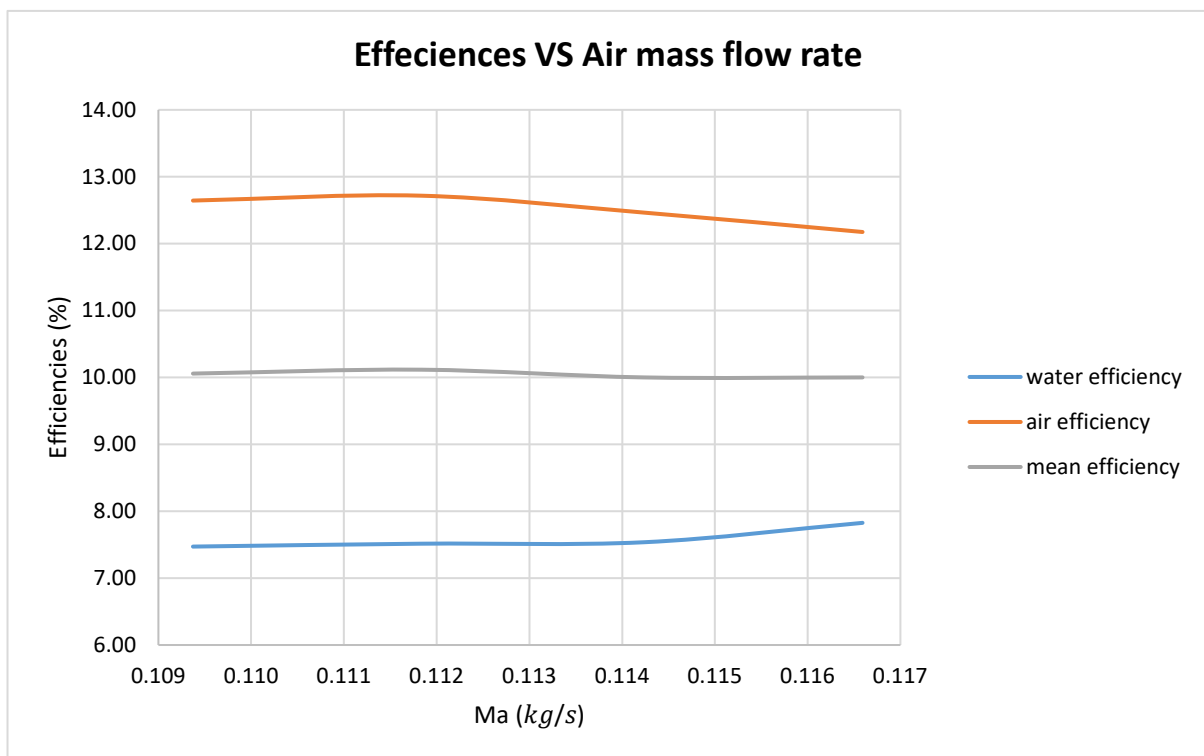


Figure 23 - Experiment 2b (Efficiencies vs Ma)

4.7 Log Mean Temperature Difference (LMTD) Data

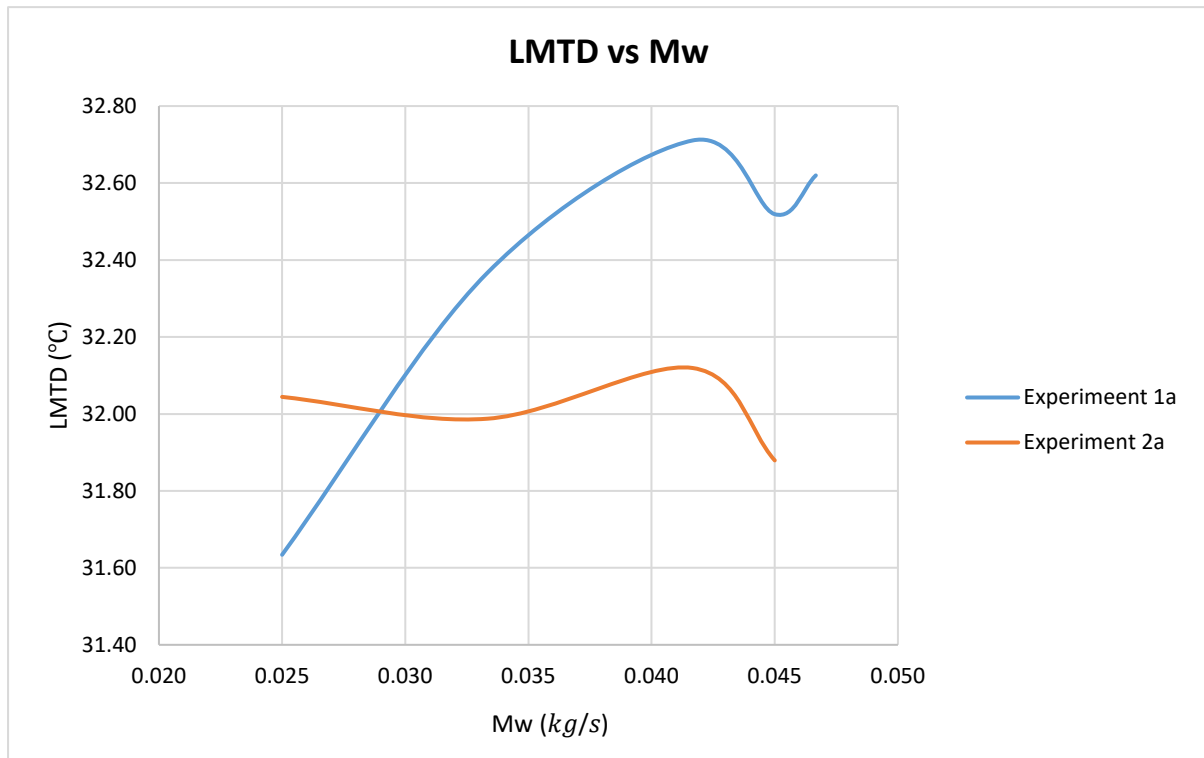


Figure 24 - LMTD data for varying water flow

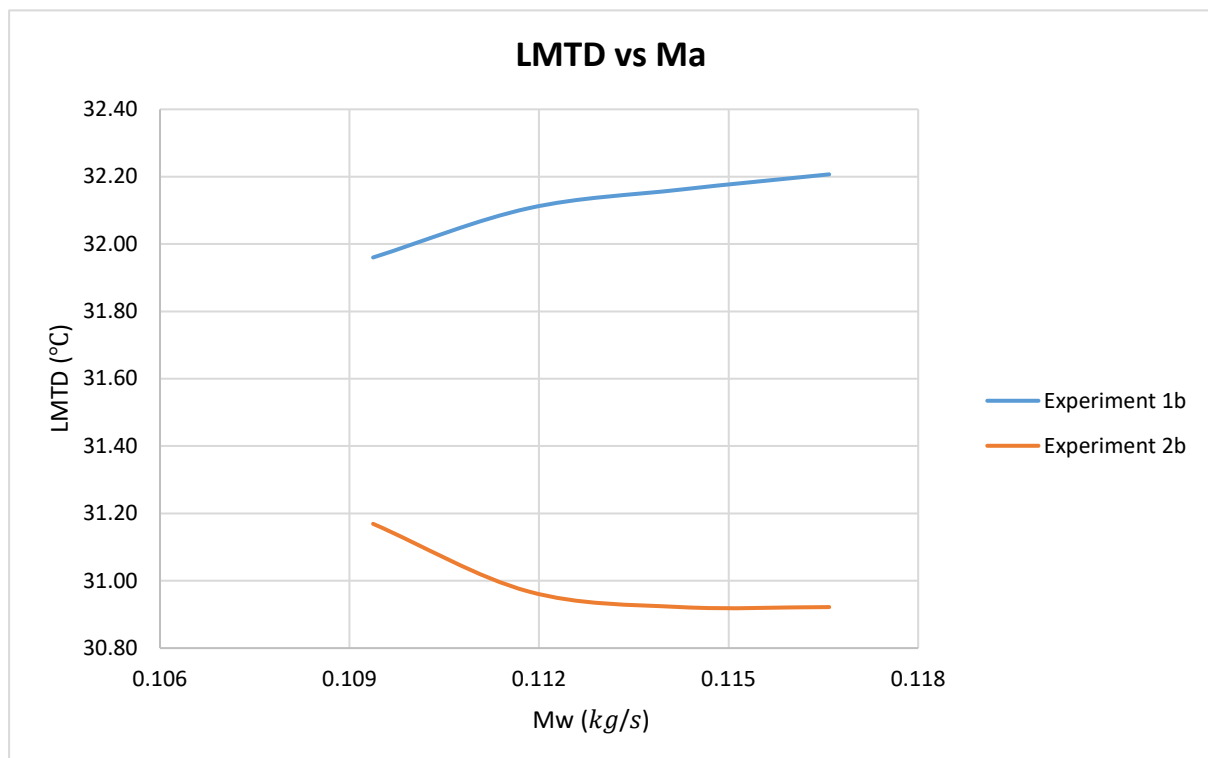


Figure 25 - LMTD for varying air flow

4.8 Analysis

It can be instantly seen from the graphical representations that the trends for the Heat Transfer Coefficient do not share the same pattern for all experiments. This shows that this parameter behaves differently and unexpectedly when varying air, water and temperature in a Heat exchanger. The Log Mean Temperature Difference graphical representations actually show similar trends for the varying air flow group and varying water flow group, the varying temperature data is more similar to the varying air flow graph. Note: The Overall Heat Transfer Coefficient (U) is found as a negative due to the temperature difference; this can be ignored and taken as absolute value so it is assumed positive.

4.9 Experiment 1a

For experiment 1a, increasing the mass flow of air seems to decrease the overall Heat Transfer Coefficient (U) until a certain point. After approximately 0.035 kg/s of water flow, the value of U happens to increase. In fact, a mass flow of air of 0.025 kg/s gives a same U value as approximately 0.043 kg/s of air. To add further, the efficiency of water and air is actually better for the initial air mass flow of 0.025 kg/s then at 0.043 kg/s, making it a better option. So it can be said that the increase of air after 0.035 kg/s is actually useless in terms of U up until 0.043 kg/s. The peak U value is seen at around 0.0347 kg/s of air which equates to an efficiency of 12.6% down from 15.5% 0.025 kg/s. This is a loss of 2.9% in mean efficiency and can be compared with other experiments to see if this loss is worth the gain in U. It is noted that although the mean efficiency has decreased, the air efficiency increases continuously as expected, but there is a concern with the mean (overall) system efficiency. This outcome has proven that increasing water flow rates does actually improve performance of the Heat Exchanger, only at a cost of efficiency.

4.10 Experiment 1b

The mass flow rate of water improves the Heat Exchanger performance until a certain point, just like in experiment 1a. However, this time after a small decrease in U, the overall Heat Transfer Coefficient continues to increase again. Between 0.112 kg/s and 0.114 kg/s the value of U decreases by $0.0005\left(\frac{W}{m^2K}\right)$, this anomaly is very small and can be completely ignored, the reason is down to the initial temperature reading, T_1 which is differs by 0.1 °C. Therefore, increasing the water mass flow continuously increases the value of U but it cannot be confirmed if this is continuous and should be a separate study. Finally, the water efficiency increases slightly as the mass flow increases which is expected, however the air efficiency de-

creases almost at the same rate that the water efficiency increases. Resulting in a mean efficiency that is technically unchanged throughout the experiment. This then makes increasing the water flow very favourable as it does not change the efficiency as the Heat Exchanger performance is increased.

4.11 Experiment 1c

It is important to note that although experiment 1c is only about heater temperature variation, the orifice pressure (air flow) was not the same as it was for the varying water flow experiment. Also, water flow is not the same value as it was for the varying air flow experiment. This may have slight changes in our outcome that is expected. The orifice pressure is 50 Pa less and the flow of water is 0.5 L/min less.

It is noticed a continuous increase in U value as the Temperature is increased 10 degrees Celsius from 30 to 40. A slight decrease in U occurs when a further 10 degrees Celsius is increased but then increases when up to 60 °C. However, the second increase does not occur at the same rate as it initially had. This can indicate that temperature increase may have an improvement on Heat Exchanger performance but only to a certain temperature. The efficiency of the water behaves the exact same way as the Heat Transfer Coefficient as temperature increases. This is expected as the temperature has a direct effect on the water. The air efficiency almost decreases by 2% and the mean efficiency overall increases by 1%. Although just a percent, this can make a difference and this shows that temperature increase does in fact improve both Heat Exchanger performance and efficiency at the same time. Unlike experiment 1a where air flow increase does improve Heat Exchanger performance but decreases efficiency.

4.12 Experiment 2a

The same as experiment 1a only using half the heat transfer area, with 16 tubes rather than 32. Instantly it is noticed that the overall Heat Transfer Coefficient increases unlike experiment 1a. This occurs and peaks up until 0.033 kg/s before then decreasing rapidly, to the point where the value of U is lower than the initial value used. Although it then increases again the rate is not as large as it initially was before the decrease of U. The efficiency of the water decreases continuously and rapidly in comparison to the increase of air efficiency. Therefore, the overall mean efficiency decreases from an initial 12% to 10% as the water flow increases.

This again is a similar behaviour to the results found in 1a however; note that the overall Heat Transfer Coefficient is very different between the two experiments.

4.13 Experiment 2b

The trends seen in this experiment are virtually the same as the trends found in experiment 1b with the only difference being the values of the overall Heat Transfer Coefficient. Although experiment 2b seems to be unchanged in terms of U for the first few changes in air mass flow rate before making a rapid change after 0.114 kg/s. The speak U parameter is then at the maximum air flow rate which is 0.117 kg/s. In fact, the overall mean efficiency is virtually unchanged as the air mass flow rate increases. So the Heat Exchanger performance has increased by an overall Heat Transfer Coefficient by 0.008, this is a 4% increase in performance with no change in efficiency, loss or gain.

4.14 Comparison

There is a concern with the Heat Exchanger performance and this can be summarized by the overall Heat Transfer Coefficient and the efficiencies of the Heat Exchanger system. From the literature review it is known that a higher value of U equates to a better Heat Exchanger performance. So the data can be tabulated for comparison between the experiments (U is denoted as absolute values (positive)):

Table 8 - Peak Heat Transfer Coefficient performances

	Experiment				
	1a	1b	1c	2a	2b
Heat Transfer Coefficient $\left(\frac{W}{m^2K}\right)$	0.138	0.139	0.129	0.201	0.195
Mean Efficiency (%)	12.6	13.0	13.9	10.9	10

Table 7 shows that the best Heat Exchanger performance was found using experiment 2a – the variation of water flow for a 16 tube Heat Exchanger configuration. However, this experiment has amongst the lowest efficiencies of the experiments. So although achieving this value of U is preferred, the system will not be very efficient in doing so. However, a mean efficiency of 12.1% is achievable for experiment 2a but at a cost of a lower U value, 0.193. Despite this reduction in U, it is still greater than most experiments with a similar efficiency. Based on this

it can already be concluded that 2a is better than 2b that is increasing water flow for a 16 tube configuration performs better than air flow for the same configuration.

The least efficient Heat Exchangers are the ones that have only 16 tubes rather than 32. This is not to be expected as mentioned in theory however could be to do with its configuration (parallel vs series connection). This shows that a decrease in Heat Transfer area directly affects the efficiency of the system as the fundamental formula states however it should increase not decrease. The most efficient system is the ones that have a larger Heat Transfer area but unfortunately in this case happen to have lower Heat Transfer Coefficient values. The best value of U with a 32 tube configuration happens to be 1b, which varies air flow. It also has the best efficiency of the other systems but has $0.054 \left(\frac{W}{m^2K} \right)$ less than 2a which is a 28% decrease in U for a 0.9% loss in efficiency. It is then reasonable to say that increasing the performance of the Heat Exchanger by over a quarter while losing out on 0.9% on efficiency is best for the Heat Exchanger performance.

Chapter 5

Limitations and Recommendations

As with every scientific experiment, there are limitations and improvements that could have been made. One of the most obvious limitations was the variation in water, air and heat values due to the TD1007 maximum limit. This meant that it could not be seen how the Heat Exchanger would perform at further increases in mass flow or heater temperature. This is clear from the graphical representations which do not show a clear trend and happen to decrease and increase in U randomly. Using more increments between the values of mass flow and heater temperature could have helped understand this random change in U also. It was mentioned that experiment 1c was unfortunately not conducted with the same orifice pressure and water flow as the other experiments which lacks consistency and unreliable results. Finally, the ambient pressure was not consistent throughout the experiments as they were conducted in one sitting as mentioned within the procedure. This is due to the availability of the Heat Exchanger which was used by others also and had to be done on separate sittings.

It is recommended that the experiments are to do done in one sitting and ensuring the Heat Exchanger used is not used by others. This will give consistent results and a fair comparison between the data found. Also the mistake found in experiment 1c which does not have the same orifice pressure and water flow.

Further investigations can include finned Heat Exchangers also which are said to further improve the Heat Transfer Coefficient, as well as using more than one Heat Exchanger for reliability. Lastly, using a Heat Exchanger that does not limit the variation of mass flow is important; this was the case as the TD1007 is designed for student experimental use.

Chapter 6

Conclusion

The aim of this project was to identify the behaviour of Heat Exchangers under different parameter changes. Changes in Heat Exchanger behaviour were successfully seen as well as identify the best Heat Exchanger configuration in terms of Heat Transfer area, mean efficiency and the overall Heat Transfer Coefficient.

Note that out of the 5 experiments conducted, the best Heat Exchanger configuration to use is 2a, that is the 16 tube Heat Exchanger with varying water flow. To be exact, a hot water flow of 2 L/min or 0.0333 kg/s with an air mass flow of 0.1166 kg/s (orifice pressure 250 Pa) and heater temperature of 60°C. Which provided a Heat Transfer Coefficient of $0.193 \frac{W}{m^2K}$ for an efficiency of 12.1%.

The theory has proven to be true although some outcomes happen to be against. For example, theory states that increasing heat transfer area improves the performance of the Heat Exchanger, should then see that the 32 tube configuration has the best performance in terms of Heat Transfer Coefficient. This is not the case and the better values are found in experiments 2a and 2b (16 tube configurations). This could be down to an error in the experiments, a mistake in the calculations or a misrepresentation in the graphs. This should be the focus for future experiments to understand the actual benefit of changing the heat transfer area.

Finally, note that the TD1007 water to air Heat Exchanger is a useful device and has been successful in the investigation and research of Heat Exchanger performance. The TD1007 has provided this data and to carry out the study.

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Appendices

Sample calculations – Experiment 2a

The following are sample calculations from experiment 2a, the first row calculations (1.5 L/min).

$$\dot{m}_w = \text{volume flow} / 60000 \times \rho_w = \dot{m}_w = 1.5 / 60000 \times 985 = 0.0250 \text{ kg/s}$$

$$\dot{m}_a = C_d \times A_0 \sqrt{\Delta p \times 2 \times \rho_a} = 0.6 \times 0.008 \sqrt{250 \times 2 \times 1.18} = 0.1166 \text{ kg/s}$$

$$\eta_w = \frac{T_{w1} - T_{w2}}{T_{w1} - T_{a1}} \times 100 = \frac{60.1 - 56.1}{60.7 - 24} = 12.53\%$$

The same method is used for the efficiency of air.

$$\dot{Q}_w = \dot{m} \times c_p \times \Delta T = 0.025 \times 4.183 \times (-4.6) = -0.481 \text{ W}$$

The same method is used for the rate of heat transfer of air.

$$C_{EB} = \frac{\dot{Q}_a}{\dot{Q}_w} = \frac{503.85}{-0.481} = -1047.4$$

$$LMTD = \frac{(T_{WX} - T_{AX}) - (T_{WY} - T_{AY})}{\ln \left(\frac{T_{WX} - T_{AX}}{T_{WY} - T_{AY}} \right)} = \frac{(60.7 - 24) - (56.1 - 28.3)}{\ln \left(\frac{60.7 - 24}{56.1 - 28.3} \right)} = 32.04 \text{ } ^\circ\text{C}$$

$$U = \frac{\dot{Q}}{A \times LMTD} = \frac{-0.481}{0.0779 \times 32.04} = -0.193$$